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URBAN CLIMATOLOGICAL STUDIES

Prepared for:

OFFICE OF CIVIL DEFENSE
OFFICE OF THE SECRETARY OF THE ARMY
WASHINGTON, D. C. 20310

CONTRACT OCD-DAHC-20-67-C-0136
UNDER WORK UNIT 1235A

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By: F. L. LUDWIG and J. H. S. KEALOHA

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Urban Climatological Studies

By F. L. Ludwig and J. H. S. Kealoha, Stanford Research Institute, March 1968. Prepared for Office of Civil Defense, Department of the Army, Office of the Secretary of the Army, Washington, D.C., under Contract DAHC-20-67-0136, Work Unit 1235A.

SUMMARY

This report reviews a research program which has studied the effects of urbanization on the distribution of temperature and humidity. The results show that available weather data, usually from airports, can be more accurately applied to the planning of shelter ventilation requirements and shelter occupancy levels. Fallout shelters are generally located in city areas where meteorological data are not available. The results of this research have provided useful relationships by which the available data at other points in the city can be used for estimates of temperature in downtown areas.

The conclusions in this report have come from two sources: from available literature on urban climatology and from a field measurement program undertaken to supplement existing data in the literature. A large number of papers, reports, and books have been studied so that we could compile as much material on this subject as possible. Many of these documents have been listed in an 82-item annotated bibliography. The findings of the literature review are presented in an appendix and are discussed in terms of the basic physical processes which affect temperature and humidity in an urban area. These processes include the heat transfer mechanisms of radiation, conduction, convection, and advection, and the moisture transfer mechanisms which are generally limited to convection, advection, and the temperature of the surface. The effects of city morphology on heat and moisture transfer are also discussed in this appendix.

The available literature was found to emphasize nighttime effects on the urban temperature fields, but there was little information on daytime effects and even less on the distribution of humidity in urban areas. A field program of temperature and humidity measurement was organized to provide more information on these topics. The first year of the study included measurements in New Orleans, Albuquerque, and San Jose, California, and the results were covered in an interim report.*

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* Ludwig, F.L., Urban Climatological Studies, Interim Report No. 1, Stanford Research Institute, prepared for Office of Civil Defense under Contract OCD-PS-64-201, Work Unit 1235A, February, 1967.

The current report describes the field program conducted in Dallas during July and August of 1967. The earlier work revealed the necessity for the study of a city which was not as affected by topographical features as were those surveyed earlier. The process by which Dallas was selected is described in an appendix to the report. For purposes of comparison with Dallas, some simultaneous measurements were made in Ft. Worth and Denton, Texas.

The data collected during the field program were analyzed, and some of the features commonly found in the analyses are discussed. To illustrate the features, and the effects of weather on them, three cases are presented and discussed in detail. One of those presented is for a clear day where the downtown center is the warmest area at night and the commercial areas of three- to four-story buildings and parking lots are warmest during the day. Another case, where the day was cloudy, shows qualitatively the same features but with smaller temperature gradients; rates of change of temperature on this day were also less than on sunny days. The third case illustrates the effects of a weather front passing through the area. In this case the same features observed on other days were still apparent, but were distorted as the front passed slowly through the region. The fields of absolute humidity for these three cases are also discussed in the report. There was some regularity in the diurnal cycle of absolute humidity, but small changes in the balance between surface moisture and the flux to higher levels could alter the cycle substantially. In general, maximum absolute humidities were observed near the time of minimum temperature and vice versa. Most topographical and urban features are not strongly reflected in the humidity fields, but the effects of a small lake were noted.

In addition to the case studies presented in the text, there is an appendix which contains the analyses of the other data collected during the 1967 summer field program.

The results of the field program and the results of other studies reported in the literature were used to investigate the magnitude of urban temperature and humidity effects. From the results obtained on this program, and from a few. less detailed studies in the literature, it was determined that daytime urban effects on temperature are only slightly related to other meteorological parameters. As noted above, certain sections of the city tend to be warmer than the environs, but the differences are generally only about 1° C.

It was found that nighttime urban effects on the temperature field were generally more pronounced than daytime effects and certainly more closely related to other meteorological factors. Study of the data from this program and from other sources showed that the nighttime urban-rural temperature difference could be as large as 9°C and was highly correlated with the rural lapse-rate (i.e., the rate of change of temperature in the vertical). The linear correlation between the two was found to be better than -0.8. The report presents three regression equations for cities grouped according to their population. These equations are based on 78 cases from 12 cities and specify urban-rural temperature differences as functions of rural lapse rate with root mean square errors of 1°C or less.

CONTENTS

CONTENTS (Concluded)

ILLUSTRATIONS

ILLUSTRATIONS (Concluded)

TABLES

I INTRODUCTION

A city, because of its buildings and topography, is capable of creating its own climate which differs from that of the surrounding rural area. Wintertime and nighttime evidences of this urban climatological effect are patterns of warmer temperatures within the city compared to the surrounding areas. This is the characteristic "urban heat-island." Past studies of this phenomenon, however, have not analyzed midday, warm weather conditions. Thus, when Office of Civil Defense shelter planning programs reached the stage where ventilation requirements during warm weather had to be ascertained, there was some doubt about the magnitude of any anomalous summertime effects on the urban climate. This research program was designed to meet the problem of determining the magnitude of summertime urban temperature and humidity anomalies.

The approach which has been taken in this research has been along two lines, a field program of temperature and humidity measurements in several cities and a detailed study of available literature on urban climatological experiments. As expected, the field program has provided substantial amounts of new data on daytime and warm weather conditions. Thus, it has been possible to develop methods of using existing climatological data to determine temperatures in various parts of a city. The usefulness of this result becomes apparent when it is pointed out that the climatological data usually identified with an urban area are taken only at a single location and this is usually at the airport on the edge of town.

This report is devoted primarily to summarizing existing information, reporting the results of recent field studies, and developing methods for estimating urban temperatures from other meteorological measurements. The instrumentation and data reduction methods employed

in the research have been described in the Interim Report (Ludwig, 1967) for this project.

Several supplementary appendices have been prepared so that original results can be emphasized in the body of the report, while at the same time the background information is in the appendices for those who wish to examine the results in more detail. Appendix A gives some of the reasoning behind the selection of field sites and gives a resume of the methods and instrumentation used in the field. Appendix B contains detailed analyses of data collected on the program. Appendix C presents a summary of the physical processes that, in combination with urban features, determine the distribution of temperature throughout a city. A similar discussion of urban humidity is also given. Most of the material in Appendix C has been gleaned from other sources, and we feel that by organizing this material to show the processes involved, it may help to clarify some of the features of the urban temperature and humidity fields which have been observed. Appendix D extends the annotated bibliography which was compiled in the Interim Report (Ludwig, 1967). Many new items have been added.

II FIELD TEMPERATURE AND HUMIDITY STUDIES

A. Field Program Planning and Operations

The results of the 1966 field program (Ludwig, 1967) indicated several areas where the study could be improved. First, the diurnal variations in urban effects were inadequately defined by the type of scheduling which had been used, and second, the cities chosen had terrain features which tended to mask the urban effects. In this year's program, these defects have been corrected.

During the summer of 1967, data were collected on a nearly round-the-clock basis. This necessitated less frequent and less comprehensive coverage of the city in comparison to the 1966 program. However, the coverage has proven to be adequate for the analytical methods used.

Dallas was selected for the field work because it is a large city, relatively flat and without large bodies of water nearby. The city's climate is such that we could expect more hot weather and fewer days of rain than for the other areas considered. The dense downtown section with its tall buildings (See Fig. 1) was also a factor in favor of Dallas. The proximity of Ft. Worth, a city of about half the population of Dallas, was also desirable because the two different size cities could be compared. A full discussion of site selection for this year's program is given in Appendix A.

Wet-bulb and dry-bulb temperatures were recorded during traverses of a preselected route in the city. The temperature records were marked at numbered points along the route to show time and location. The route and the numbered points for Dallas are shown in Fig. 2. This map shows the topography and the built-up areas. Also shown are two straight lines upon which the numbered points are projected. These straight lines serve as the base for the time sections that were used in the data analysis. The

FIG. 1 AERIAL VIEW OF DALLAS

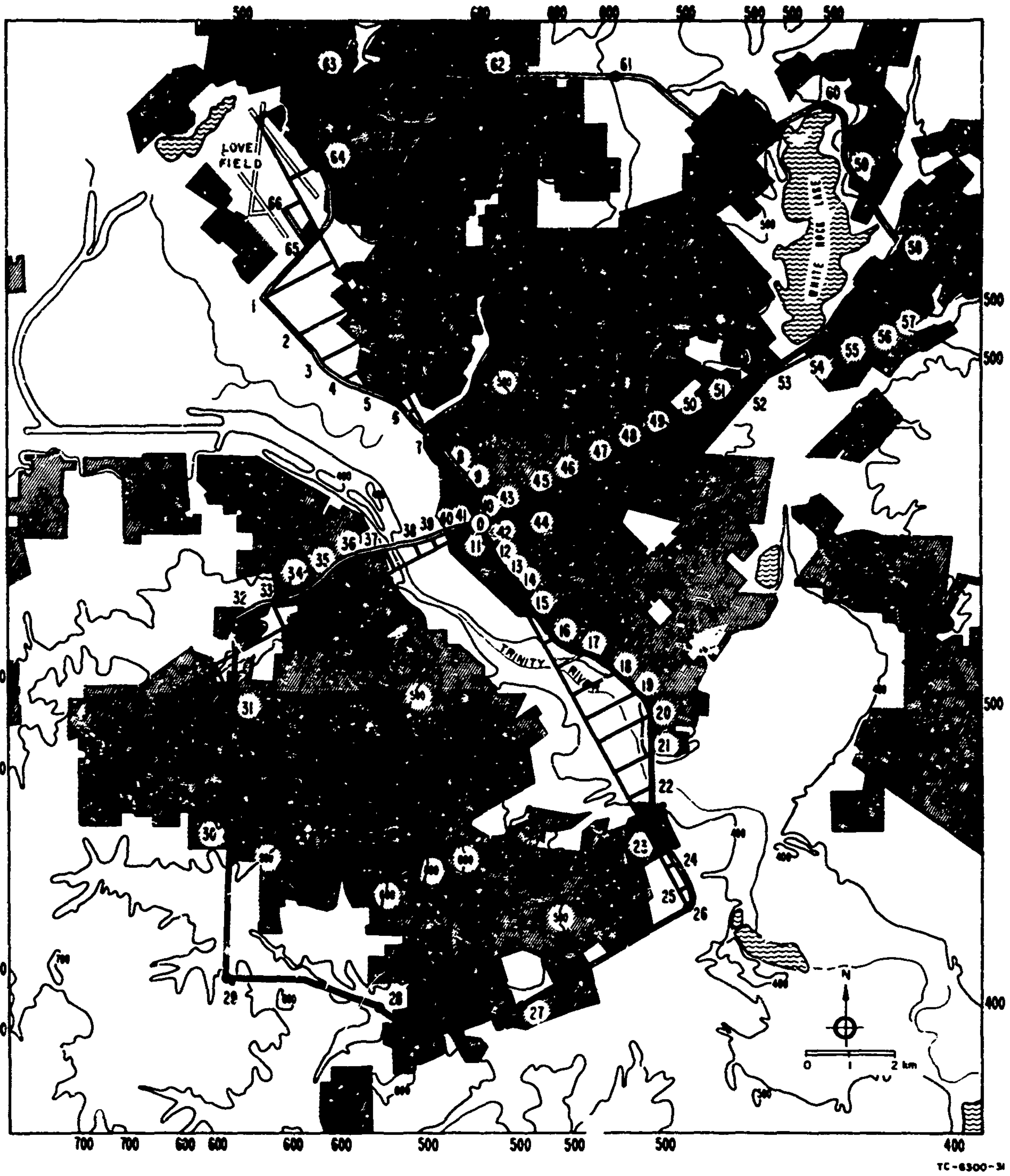

FIG. 2 DALLAS ROUTE

intersection of these two lines is at the center of the downtown area. An aerial photograph of Ft. Worth and the routes used there are shown in Fig. 3 and 4. The Dallas and Ft. Worth routes are discussed in detail in Appendix A.

Temperatures were measured at 0.3 and 2 meters with ventilated thermistor elements mounted on the front bumper of the test vehicle. System accuracy was about ±0.25°C. Response times were about 10 seconds for the dry-bulb element and 30 seconds for the wet-bulb element. Occasionally, extraneous heat sources such as auto exhausts made temperatures at the 0.3 meter level somewhat unrepresentative, and so only the 2-meter temperatures have been used in the analyses presented in this report. The instrumentation is the same as was used for the 1966 measurement program and described in the Interim Report (Ludwig, 1967).

In addition to the mobile temperature measuring equipment, two fixed instruments were used. These were placed on the roof of the terminal building at Love Field in Dallas. A standard hygrothermograph, placed in a U.S. Weather Bureau instrument shelter, provided some temperature information that was useful for interpolation purposes in the data anlysis. The other fixed instrument was a pyrheliograph. In this report, the insolation records from this instrument have been used primarily for qualitative interpretation of results.

The official hourly observations made at several locations in the Dallas-Ft. Worth area were also available and have been used in the analyses.

B. Data Analysis Techniques

In the past, the results of urban temperature distribution studies have usually been presented in one of two basic formats. In one scheme data are collected at different times in different locations in the city and then, for each location, interpolation is used to estimate the temperature at some time common to the entire area. The results are then interpreted by

FIG. 3 AERIAL VIEW OF FT. WORTH

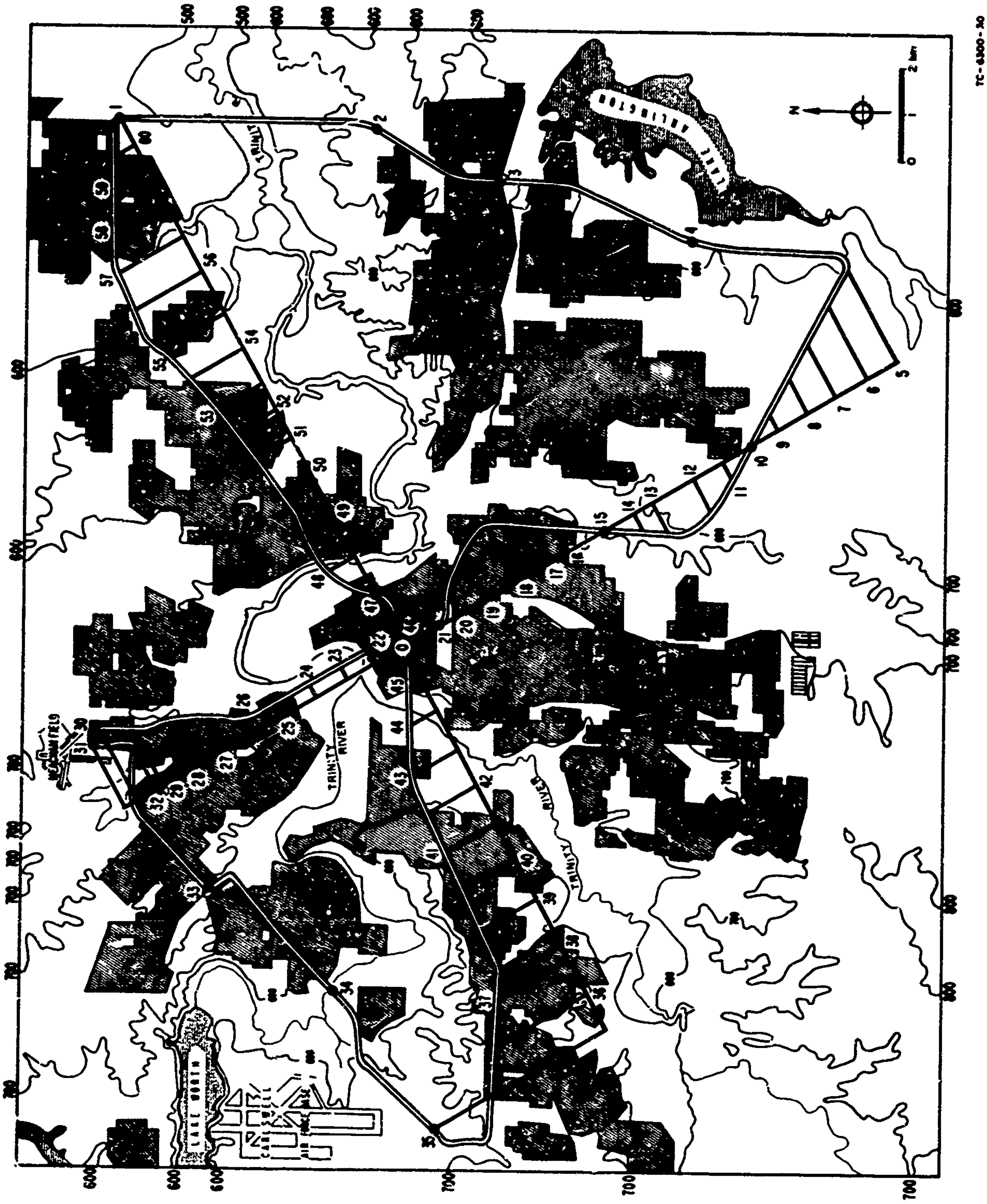

FIG. 4 FT. WORTH ROUTE

an isotherm analysis of the temperature distribution at the common hour. In the other commonly used scheme, temperatures are measured along a single line through the city so that temperature can be graphed as a function of location. This often involves interpolation in time also.

In either scheme, temperature fields at different times must be presented in separate maps or graphs. Examples of these two formats include the maps for different hours of the day given in the Interim Report for this program (Ludwig, 1967) and the graphs of temperature versus location for several different times given by Sundborg (1951).

A third type of presentation has been used by Ludwig (1967). In this scheme, the temporal variation of temperature at different sites is plotted in individual graphs for each site. Thus the temporal variation of temperature is shown as a continuous function, but spatial variation is shown discontinuously by the separate graphs for the different locations. The presentations using maps or graphs of the temperature field at different hours show the spatial changes in a continuous fashion and the temporal changes discontinuously.

Besides the fact that either the temporal or the spatial changes in temperature are presented discontinuously, there is another disadvantage to these formats. They do not allow for one-step interpolation in both space and time. In the case of successive maps, observations are first interpolated to a common time. Then the temperature field for this time is analyzed. This analysis is a form of spatial interpolation.

We felt that a more efficient analysis of the data and a more meaningful interpretation of the analyses could be obtained if the results could be presented in a form that was continuous in both space and time.

For many years, meteorologists have used a form of analysis called the vertical time section. In these analyses the temperature field is presented as a function of time and height. Radiosonde soundings from the surface to great heights are plotted at the appropriate times; then during analysis both the changes with height and time can be accounted for.

It occurred to us that a "horizontal time section" might be the ideal format for presentation of the results of urban temperature and humidity studies. In such a presentation temperatures measured at successive points along a line through the center of town are plotted at points on the graph appropriate to the location and the time of measurement. Routes in Dallas, Ft. Worth, and Denton, Texas, were planned with this presentation in mind. The San Jose routes were realigned somewhat so that they would also be suitable for this format. These routes are illustrated and described in Appendix A. For each city there are two lines through the center of town and these intersect at approximately right angles.

The temperatures were read from the strip charts recorded during trips around the routes. These were transferred to punch cards and then to magnetic tape. Records were edited for errors, and vapor pressures were calculated from measured wet- and dry-bulb temperatures. This procedure is basically the same as that used on the data collected last year (Ludwig, 1967).

The records were then plotted by automatic plotting equipment. A point is entered corresponding to a specified location on the route and time of measurement. Above the plotted point, temperature is entered in tenths of a degree Centigrade. Below the point is the vapor pressure in tenths of millibars.

In addition to the machine plotted information, other data were entered by hand. Along an edge of the northwest-southwest cross-section analyses for Dallas, the insolation has been graphed as a function of time. This information was transferred from the records of the project pyrheliograph which we operated at Love Field. The hourly measurements made at Love Field by the U.S. Weather Bureau are also shown on the Dallas analyses. These are plotted in approximately the correct location, near the northwest end of the cross-section line. The plots show the wind direction and speed, the cloud cover and the temperature.

Wind direction is shown by the shafts extending from the station circles. These indicate the direction from which the wind is blowing. On the analyses in this report, wind directions are shown in conformance

with the direction of the cross section. For example, a shaft perpendicular to the time axis indicates a wind along the cross section. In the case of Love Field data, wind would be coming from the northwest if the shaft points to the bottom of the plot. Wind speed is shown by the barbs on the direction shaft. Each full barb indicates ten knots, a half-barb, five knots. Calms are indicated by an extra circle around the station. Station circles also indicate the cloud cover. An empty circle represents clear or nearly clear skies. One vertical line in the station circle is for scattered cloudiness, two vertical lines are for broken cloudiness, and crossed lines are for overcast or nearly overcast skies. Temperatures are plotted in degrees Centigrade next to the station circles. Since the temperatures were originally reported to the nearest degree Fahrenheit the Centigrade values are only accurate to about 0.5°C even though they are shown to the nearest 0.1°C.

Similar information for Carswell Air Force Base and Meacham Field is shown in approximately the correct locations on the Ft. Worth analyses. As with the Dallas data, wind directions were plotted in relation to the direction of the cross-section line. The temperatures are also only accurate to the nearest 0.5°C.

Strip diagrams were also included on the plots to help visualize the nature of the terrain along the cross sections and to locate the points along the spatial axis. The points are shown in Figs. 2 and 4 and are identified in Appendix A. The vertical profile of the surface is shown greatly exaggerated with respect to horizontal distances. The length of each Dallas cross section is about 15 miles. Cross sections for other cities are shown to the same scale.

Sunrise and sunset times are indicated on the time axis.

The analyses show the isotherms, labeled in degrees Centigrade, as solid lines. The dashed lines are isohumes, labeled in millibars of vapor pressure.

C. Illustrative Cases

In this section, several examples of diurnal temperature and humidity cycles will be presented. The cases have been chosen to illustrate features which are commonly found in the observations, or because they illustrate one or more of the physical effects discussed in Appendix C. The cases which are not used as examples here are presented in Appendix B.

1. August 7, 1967 (Day No. 219), Dallas

a. Temperature

August 7 is a good example of the changes which take place in the temperature field on a clear day in Dallas. The insolation curve shows that the few clouds present during the day were thin and that they only slightly attenuated the incoming radiation. The winds at Love Field were generally within 30° of south during the day and had speeds around 10 kts.

With relatively light winds and clear skies the urban effects are pronounced. The temperature field for this day is illustrated in Figs. 5 and 6. Starting with the northwest-southeast cross section, Fig. 5, we see that the minimum temperatures occur shortly after sunrise, as expected. The analysis indicates that the temperature never falls as low as 28°C in the center of the city on this day, but at the northwest end of the cross section it falls well below 28°C. At the southeast end (Pt. 26) it drops below 26°C. While this particular value is somewhat speculative because of sparse data, it is reasonable in terms of results found on other days. The other warm area where the temperature does not fall below 28°C is the commercial area near the airport. However the official airport temperature drops below 28°C.

As the morning continues, the entire area warms at about the same rate, as can be seen by the relatively even spacing of the isotherms. At 1000 the center of the city is still almost a degree warmer than either end of the northwest-southeast cross section. After 1000, the

spacing between isotherms is greater in the city center than just outside the downtown area, indicating that the city is heating more slowly. This continues so that at the time of maximum temperature, the situation is almost the reverse of what it was at the time of minimum temperature; the downtown center is nearly a degree cooler than the commercial areas outside the center of town. These warm areas include the densely packed, four- or five-story buildings just northwest of the downtown center, an area near Love Field which has tall, more widely spread buildings, and, closer to the airfield, the commercial area mentioned earlier. Southeast of the downtown center there is an industrial area enclosed by the 39°C isotherm.

While the wooded residential area at the northwest corner and the open fields at the southeast are both relatively cool, the coolest afternoon location is over the wooded bottom lands of the Trinity River. This is somewhat surprising because these temperatures were measured at approximately treetop level (on a viaduct) and not in the shade below the trees. Furthermore, the Trinity River had very little water flowing, and it seems highly unlikely that the river affected the temperature. The most plausible explanation would seem to be cooling by evapotranspiration. This area commonly had one of the lower maximum temperatures along this cross section.

Cooling begins at the time of maximum temperature, and the city center is seen to cool more slowly than the environs, just as it heated more slowly in the morning. At 1600 the temperatures at the center of town and at Pt. 26 are both slightly above 38°C. By sundown, at about 1920, Pt. 26 is 1.5°C cooler than downtown. By midnight this difference is about 3°C. The differences which develop between the downtown center and the northwest end of the cross section (Pt. 63) are only about half as great as those between the center and the southeast end (Pt. 26). This may be caused by more trees and buildings at Pt. 63 than at Pt. 26. The buildings may retain heat, and a canopy of trees will insulate the lower layers from some radiative losses of heat. The retention of heat by the downtown buildings is certainly evident in the relatively slow cooling of that section of town.

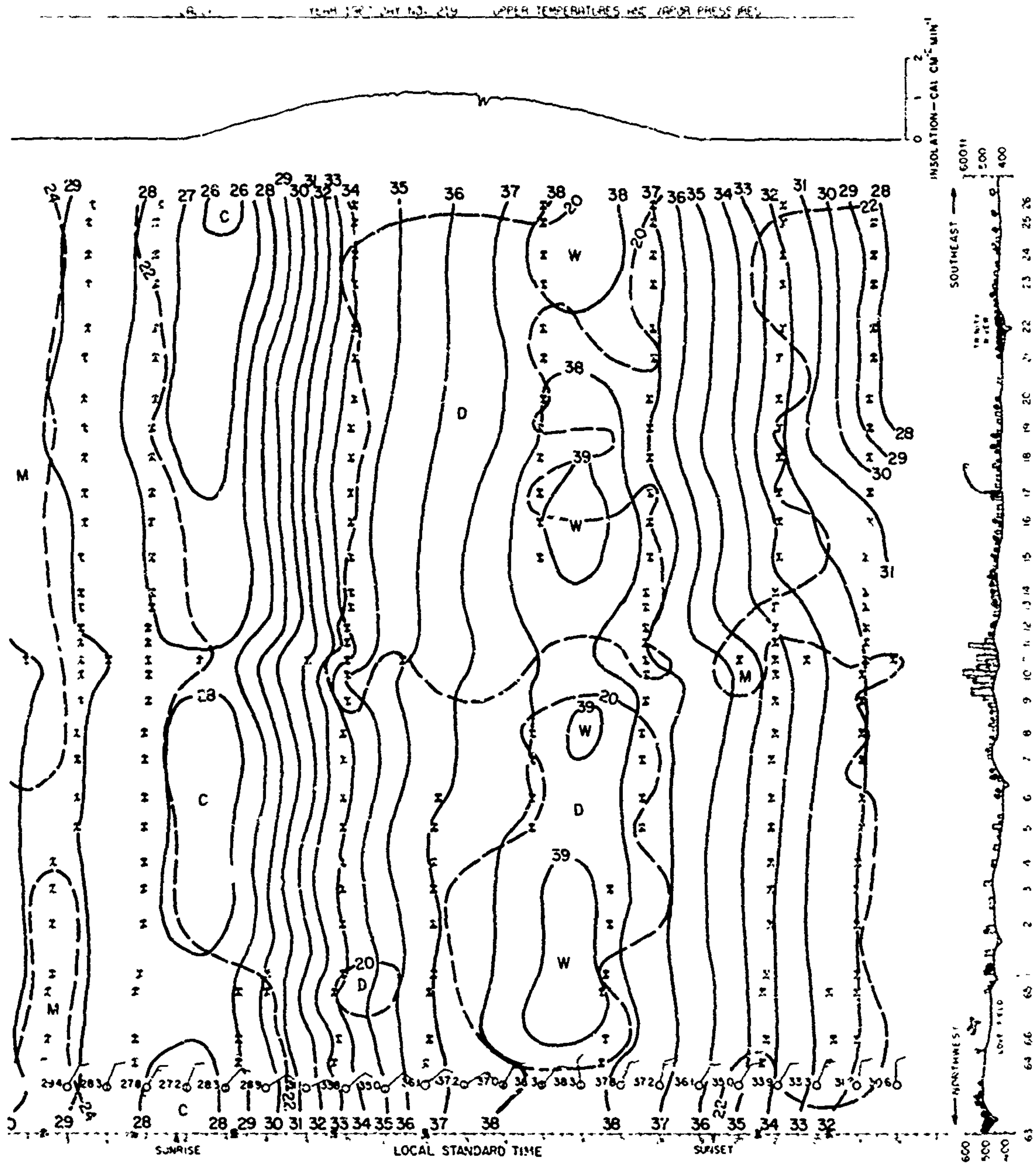

FIG. 5 DALLAS HORIZONTAL TIME SECTION, AUGUST 7, 1967, NW-SE

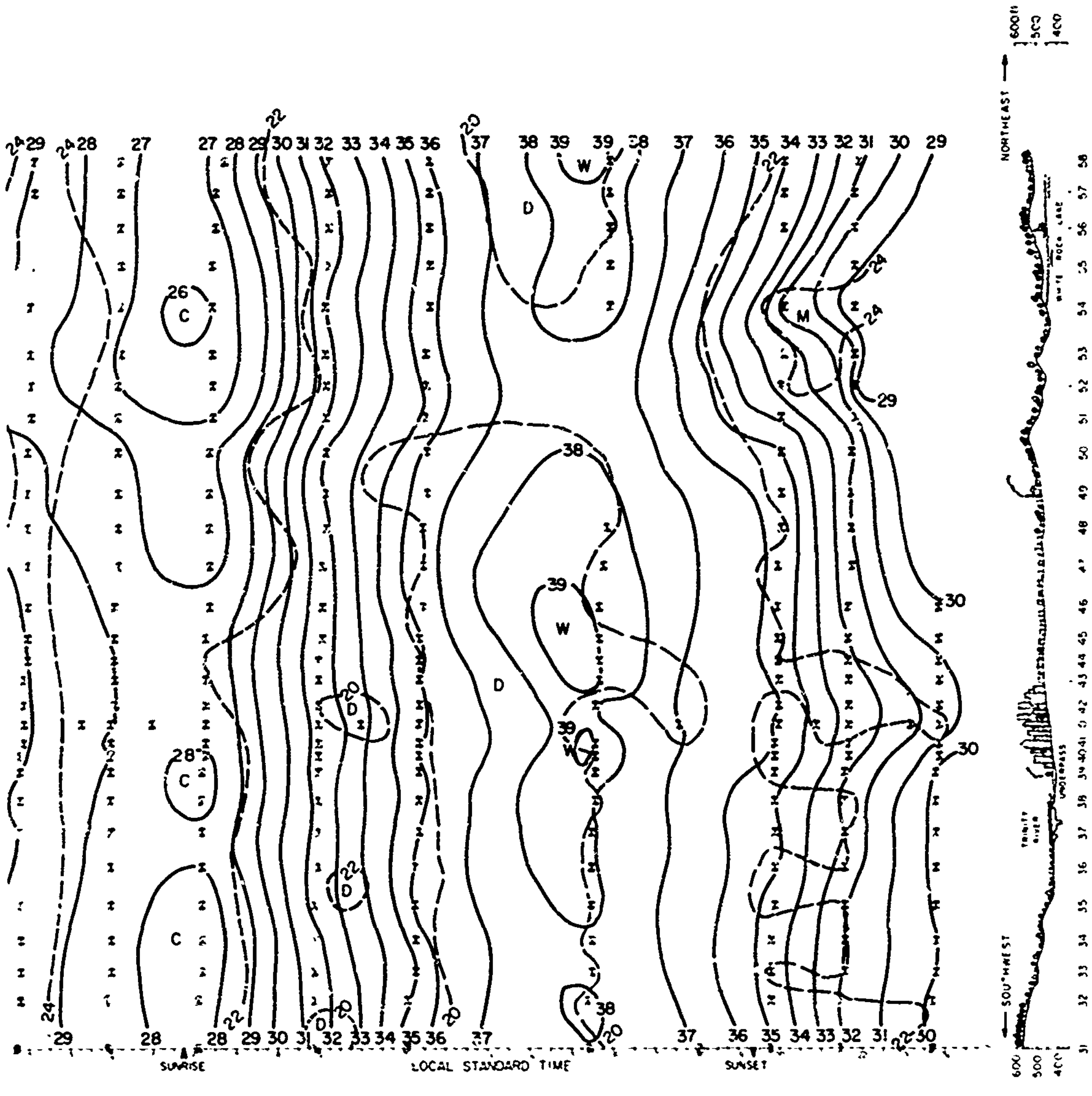

FIG. 6 DALLAS HORIZONTAL TIME SECTION, AUGUST 7, 1967, SW-NE

On the southwest-northeast cross section, Fig. 6, the same types of effects are seen as on the northwest-southeast, but they are much more pronounced. At the time of minimum temperature, the central city and the commercial area northeast of it form the warmest area along this cross section. The temperature is more than 2.5°C greater in these areas than at the coolest location in a low area just below White Rock Lake.

The cool center at Pt. 54 heats very rapidly through the morning and early afternoon; it goes from being the coolest location on the cross section to being relatively warm. This is not at all atypical. The coolest locations at night are generally around Pt. 52 or Pt. 54, but Pt. 52 usually is the coolest during the day also, whereas Pt. 54 heats more and becomes relatively warm. Point 52 is amid a moderately shaded, grassy park-like area. At Point 54, the measuring vehicle has just passed through a small commercial area with few trees and has not yet entered the park area adjacent to White Rock Lake.

Nearer the center of town the temperature behaved much the same as it did along the other cross section. The center of town has progressed from being warmer than its immediate surroundings to being cooler. Again the regions of densely packed, moderately tall buildings are warmer than the region of very tall, tightly packed buildings. If we assume that these warmer regions connect with those which were found on the other cross section, then it would appear that the center of town is a cool area surrounded by a warm ring. This feature appears in nearly all the individual cases. This effect probably reflects differences in effective absorbtivity and heat capacity. The tall buildings have large heat capacities and receive little insolation at street level and therefore heat more slowly than the four- or five-story buildings on the edge of the downtown area. These moderately tall buildings receive much insolation, both direct and reflected from neighboring buildings; it penetrates to street level, and the buildings do not have the large heat capacities of the sky scrapers.

The isotherms tend to mirror themselves about the time of maximum temperature. The areas which heated most slowly, now cool most slowly, and those which heated rapidly, now cool the same way. However, the

differences in heating or cooling are more pronounced during the cooling period than they were during the heating period. So, by 2000, the downtown region has become the warmest along the cross section; it has cooled only a little more than 2.5°C while the area around Pt. 54 has cooled more than 7°C. The rapid cooling in this area is very characteristic of this location and may be characteristic of low-lying locations in general, although the nearness of White Rock Lake may make this spot somewhat special. The rapid cooling does not continue through the night. In fact for a few hours before midnight it often stops altogether and secondary minima form; cooling then resumes after midnight, but at a much slower rate. This results in this area being much cooler than the downtown area during the early evening hours, about 5°C cooler in this case; however, as the night continues, the temperature difference becomes less and may only be about half as great at the time of minimum temperature.

b. Humidity

While the temperature patterns observed on this day were quite similar to those observed on the other days of the series, the humidity variations were not. The maximum humidity occurred around 0200 when values of vapor pressure greater than 24 mb were observed everywhere except in the area around Pt. 6, northwest of the center of town. Here the humidity approached 24 mb, but did not quite get that high. From 0200 until about 1000 the vapor pressure declined about 4 mb. The humidity then remained almost constant for about 7 or 8 hours. About sunset, or a little before, the air became more moist.

The rise in humidity in the late afternoon and early evening is reasonably typical as are the persistent and expected higher humidities in the vicinity of White Rock Lake. Atypical is the morning trend of humidity on this day. Normally, maximum humidity values are observed just after sunrise. The maximum usually occurs after a slow rise through the night, and is then followed by a decline until around the time of maximum temperature.

It is typical for the Dallas temperature and humidity cycles to be of opposite phase; maximum absolute humidity with minimum temperature, minimum humidity near the time of maximum temperature. The time of minimum humidity varies considerably from day to day, and this particular case falls within the range of the variations. However, the time of maximum humidity is generally close to sunrise, and this case is very atypical in that respect.

2. July 18, 1967 (Day No. 199), Dallas

July 18 is not at all typical of the usual temperature patterns seen in Dallas. It shows the effect of overcast, rainy conditions on urban temperature and humidity fields and on the diurnal cycle of changes in these fields. The day was typified by sporadic light showers between about 0400 and 2000. In spite of the rain, there was a significant reduction in visibility which U.S. Weather Bureau observers attributed to haze. Skies were overcast throughout the day and the pyrheliograph record shows little insolation. During most of the day, winds were from a direction between east and southeast, with speeds generally less than 10 kts until noon and between 10 and 14 kts after noon.

a. Temperature

The temperature fields are shown in Figs. 7 and 8. The most striking difference between these figures and the clear sky cases discussed in the preceding section is the much wider spacing of isotherms. The temperature changed much less both with time and with space on this rainy, overcast day than it did on the clear, sunny day.

The coldest points at the time of minimum temperature are about 2°C cooler than the center of the downtown heat-island. These cool spots are located near Love Field, at White Rock Lake, near the underpass just southwest of the downtown area, and in the relatively high, grassy park area at the southwest end of the southwest-northeast cross-section line.

The pyrheliograph trace in Fig. 7 shows that the incoming radiation was quite feeble. This results in the very weak heating which is observed. In the center of town, the temperature rises less than 3.5°C. In the area just northeast of the center of town it rises about 4.5°C--still very small compared to the values around 11°C on the sunny day.

This overcast day has one feature in common with all the sunny days. The center of the downtown section is cooler than some of the areas surrounding it. This casts some doubt on the radiative explanation we have offered for the warm ring surrounding the downtown area. If this warm ring is caused by differences in the amount of insolation absorbed by the buildings at the lower levels, then when the insolation is very small, we would expect the absorption differences to be small also. This would lead to a much less pronounced effect, but the annulus which forms on this day is almost identical to those which are observed on the other, more sunny days.

Between about 2000 and 2400 the whole city cools only about 1°C. In the wooded bottom lands of the Trinity River around Pt. 22, and at Pt. 54 just below White Rock Lake, it cools rather quickly from 24 to 23°C, but then it remains at about the same temperature for the next three hours. In the center of town and in the area northwest of it, just the opposite happens; the temperature stays about 24°C for three hours, and then drops to 23°C. Very little heat-island effect develops during the evening.

This case and the preceding one illustrate one of the effects which Chandler (1965) found in his equations for the magnitude of the urban heat-island (see Appendix C). He found a strong positive relation between diurnal temperature range and the strength of the nightime heat-island in London: On the sunny day there was a large temperature range and a strong heat-island, and on this cloudy, rainy day the situation is reversed. The relation appears to hold in Dallas, and it is not surprising because when radiative processes are allowed to dominate, low-level rural temperatures can undergo large diurnal changes. Since the great thermal

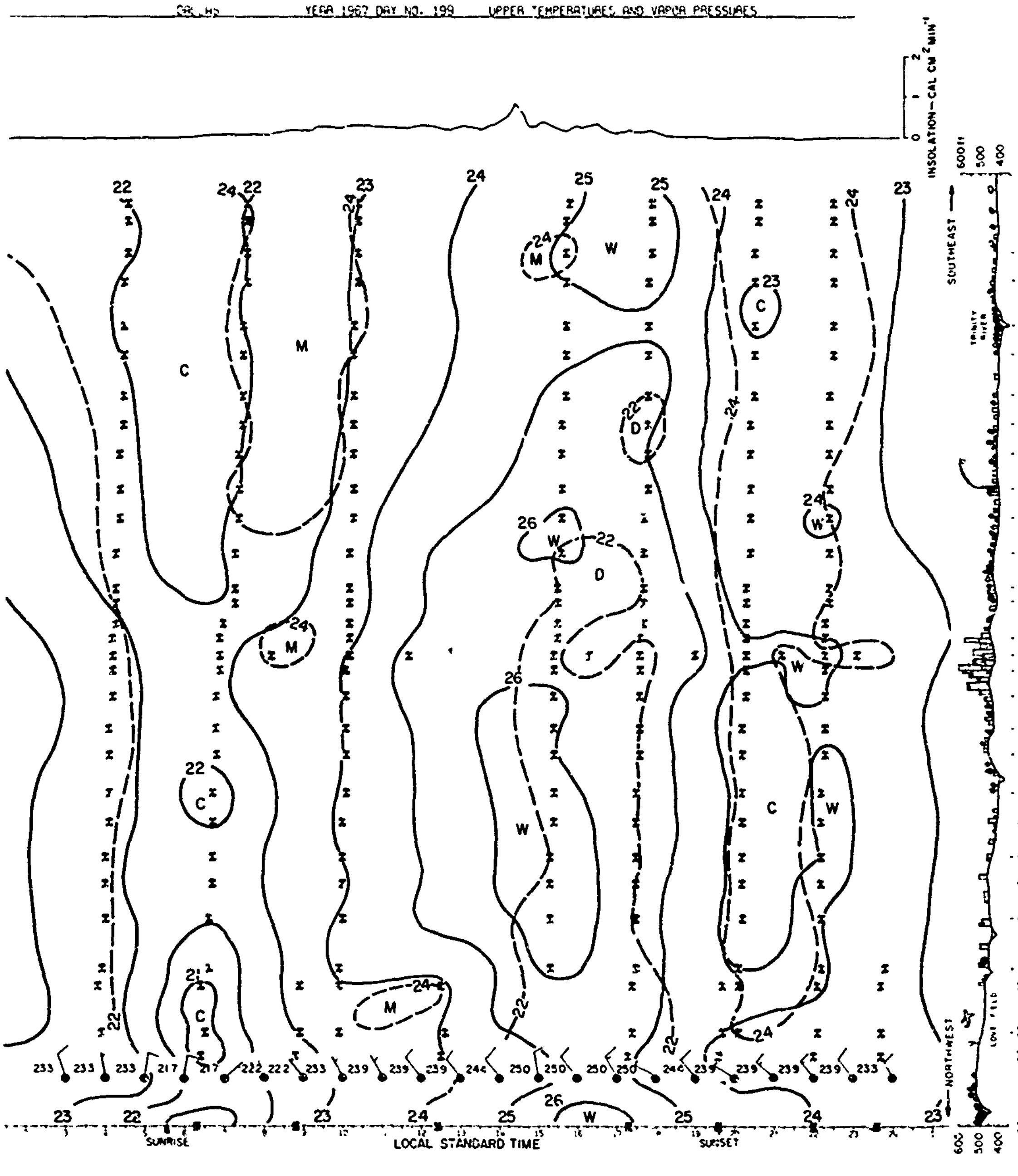

FIG. 7 DALLAS HORIZONTAL TIME SECTION, JULY 18, 1967, NW-SE

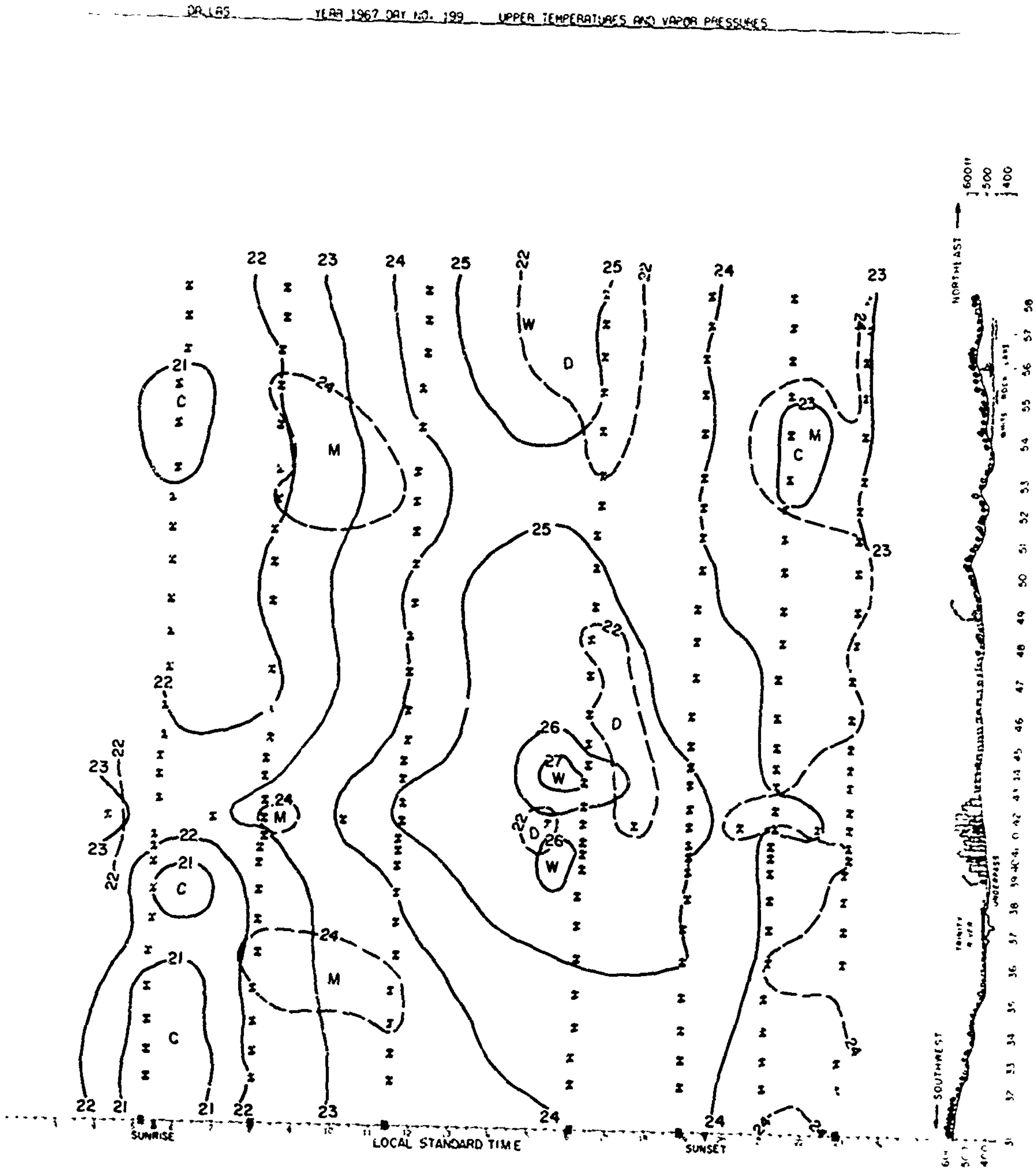

FIG. 8 DALLAS HORIZONTAL TIME SECTION, JULY 18, 1967 SW-NE

mass of the city restricts the amplitude of its temperature cycle, the strongest heat-islands will normally develop with the widest diurnal ranges of rural temperature. These two effects result from the same radiative cause.

b. Humidity

In a qualitative sense, this unusual overcast day is more typical of the diurnal Dallas humidity cycle than August 7 with its typical temperature pattern. The maximum humidities are reached between 0800 and 0900. Minimum humidities are reached just slightly after the time of maximum temperature. Humidity begins to rise through the early evening then becomes relatively constant. The usual moist area near White Rock Lake is also apparent through most of the day.

Where this case differs from the typical is in magnitude. The total range from lowest to highest humidity observed during the period is only about 4 mb. Normally, the observed fields are not so flat. Diurnal ranges are often half again as great as in this case.

3. August 4, 1967 (Day No. 216), Dallas and Ft. Worth

This day was chosen for discussion for two reasons. First, U.S. Weather Bureau analyses show that a slowly moving cold front passed through the Dallas-Ft. Worth area during the day. This front was moving from north to south and was oriented almost exactly east-west. The other reason for choosing this case is that it is one of the three times when measurements were made simultaneously in both Ft. Worth and Dallas.

If the wind directions at the airports in the area are used as indicators of the arrival of the front, the following picture develops. Winds south of the front were generally from the south to southwest. North of the front, winds were from around northeast. The front was definitely north of the area until around 0900 and was definitely south of the area after about 1700. Between these times the wind direction was variable as the slow moving front passed through the area.

Rain showers were noted north of Dallas in the late afternoon, and there was some shower activity in the city in the early evening.

a. Temperature

Figures 9 and 10 show the Dallas cross sections for August 4, 1967. One of the most obvious features of these diagrams is the rapid cooling in the late afternoon. In some parts of the city, the temperature drops 10°C in the four hours between 1530 and 1930. This contrasts with about 6°C for the most rapidly cooling area, near White Rock Lake, for the typical case that has already been discussed. Undoubtedly, this day's rapid cooling represents a combination of the normal processes and the frontal passage.

Another apparent effect of the frontal passage is the disruption of the usual processes which work toward the development of organized urban thermal fields. This disruption seems most pronounced in the center of town. Between 0800 and 0900 there is very rapid heating, but then the temperature drops somewhat between 0900 and 1000. It is possible that similar fluctuations occurred elsewhere in the area, but the time between observations does not allow the resolution of such details except downtown where measurements are made twice as often. Another possible explanation is that the front made a tentative excursion into the area; the wind shifted from south to west-northwest at Love Field just before 0900. In the center of town the temperature reached a maximum just before 1400, then it dropped until about 1530, and it finally rose again to another maximum shortly after 1600. This period was characterized by substantial variability of wind direction at Love Field. The temperature oscillations in the center of the city may reflect the greater frequency of the observations there, but it might also be a real effect. If real, it would indicate that the heavily built-up area was more sensitive in its response to the mesoscale temperature fluctuations accompanying the frontal passage.

It should also be noted that the features seen in the typical case are discernible on this day also, but they have been distorted by the larger scale weather patterns. The heat-island is quite evident at the time of minimum temperature. During the afternoon, the relatively cool

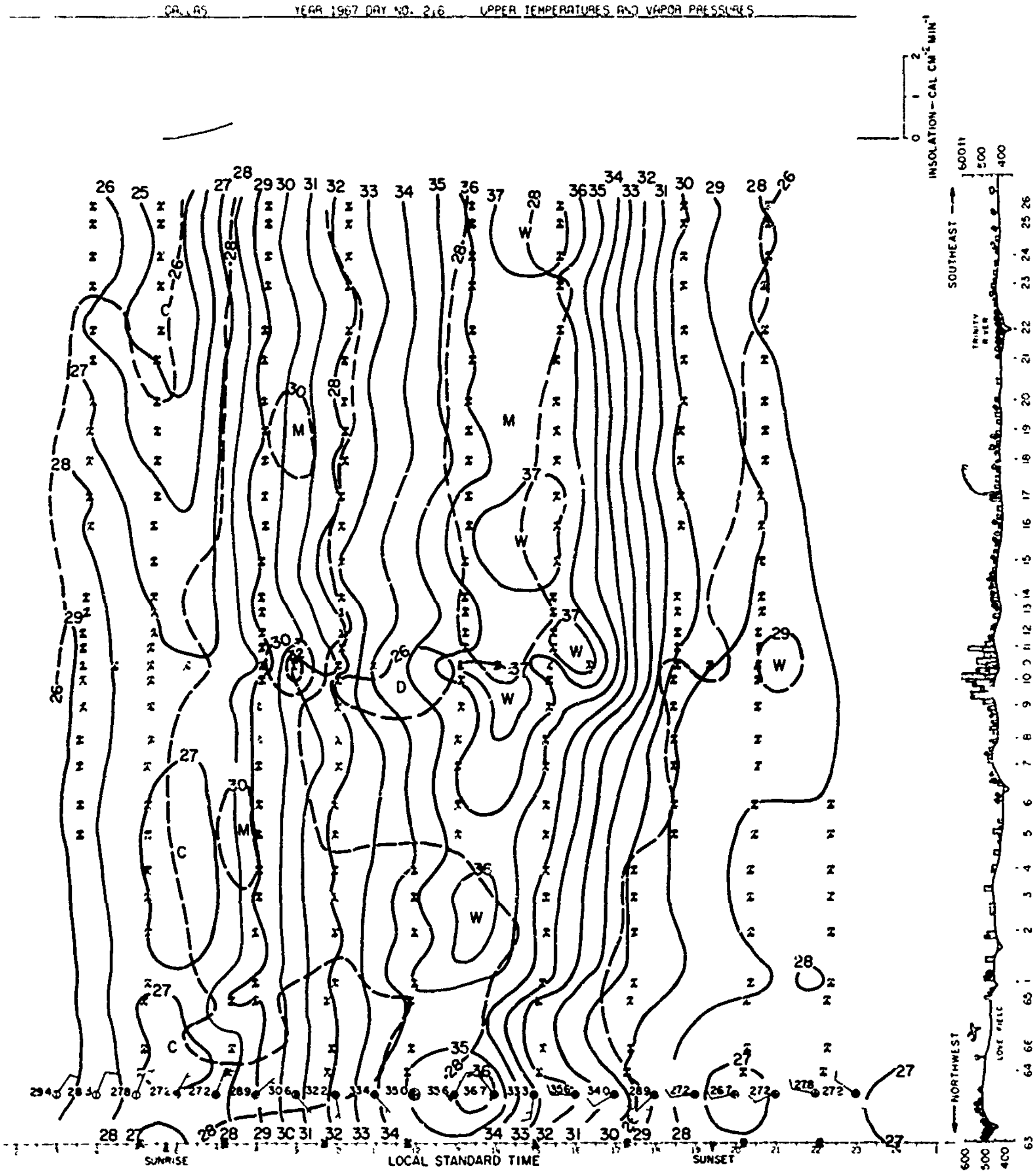

FIG. 9 DALLAS HORIZONTAL TIME SECTION, AUGUST 4, 1967, NW-SE

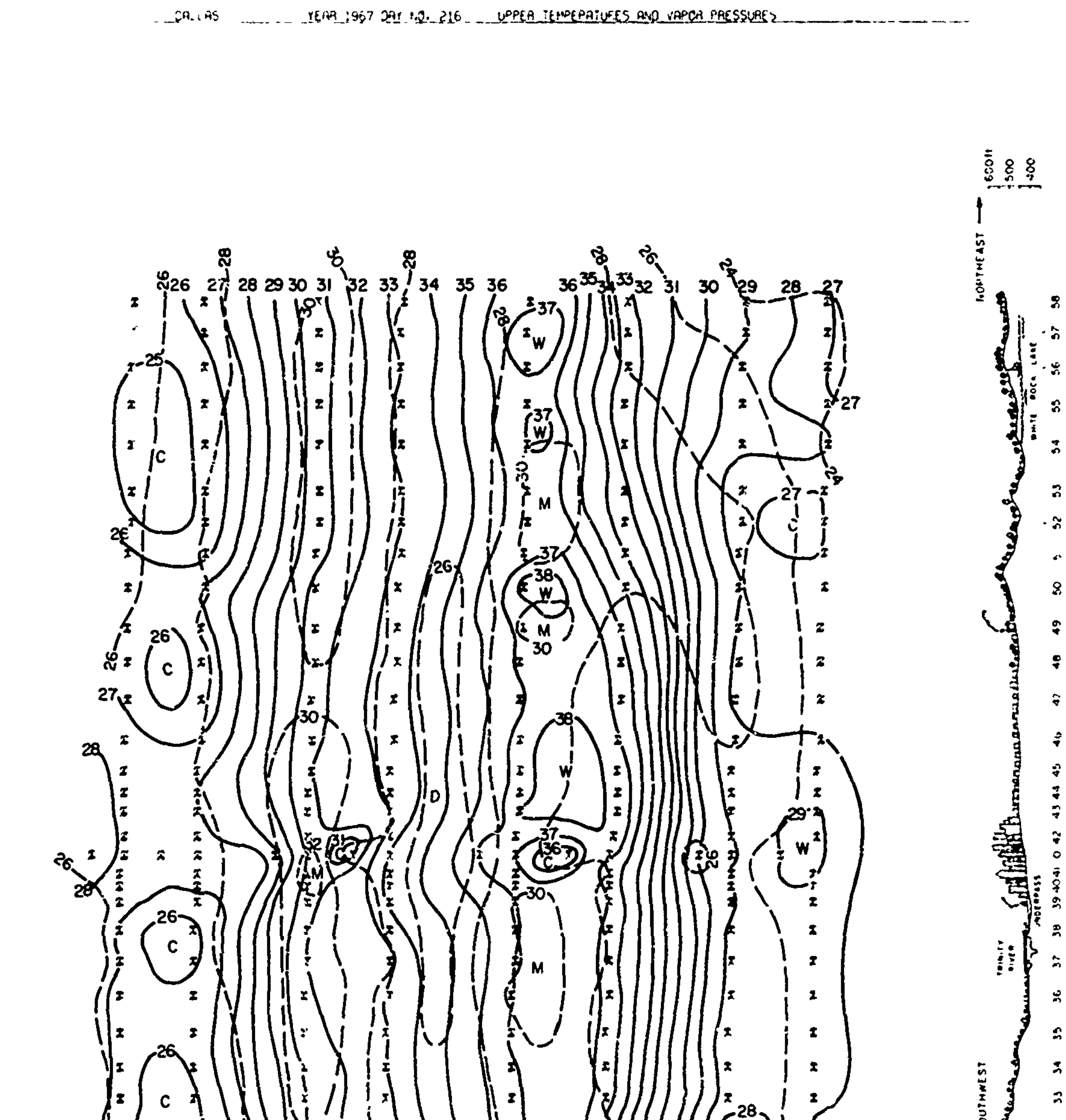

FIG. 10 DALLAS HORIZONTAL TIME SECTION, AUGUST 4, 1967, SW-NE

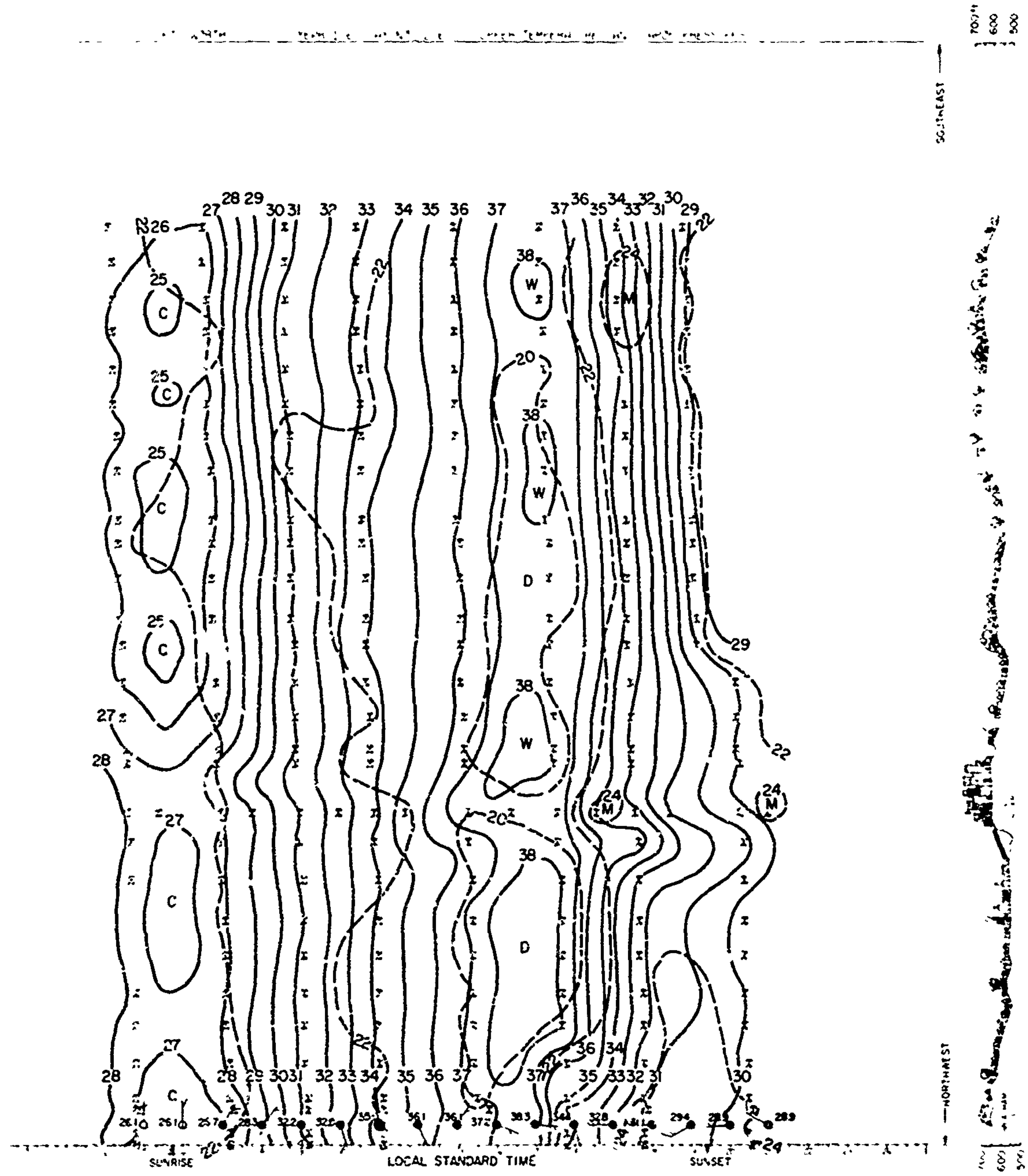

FIG. 11 FT. WORTH HORIZONTAL TIME SECTION, AUGUST 4, 1967, NW-SE

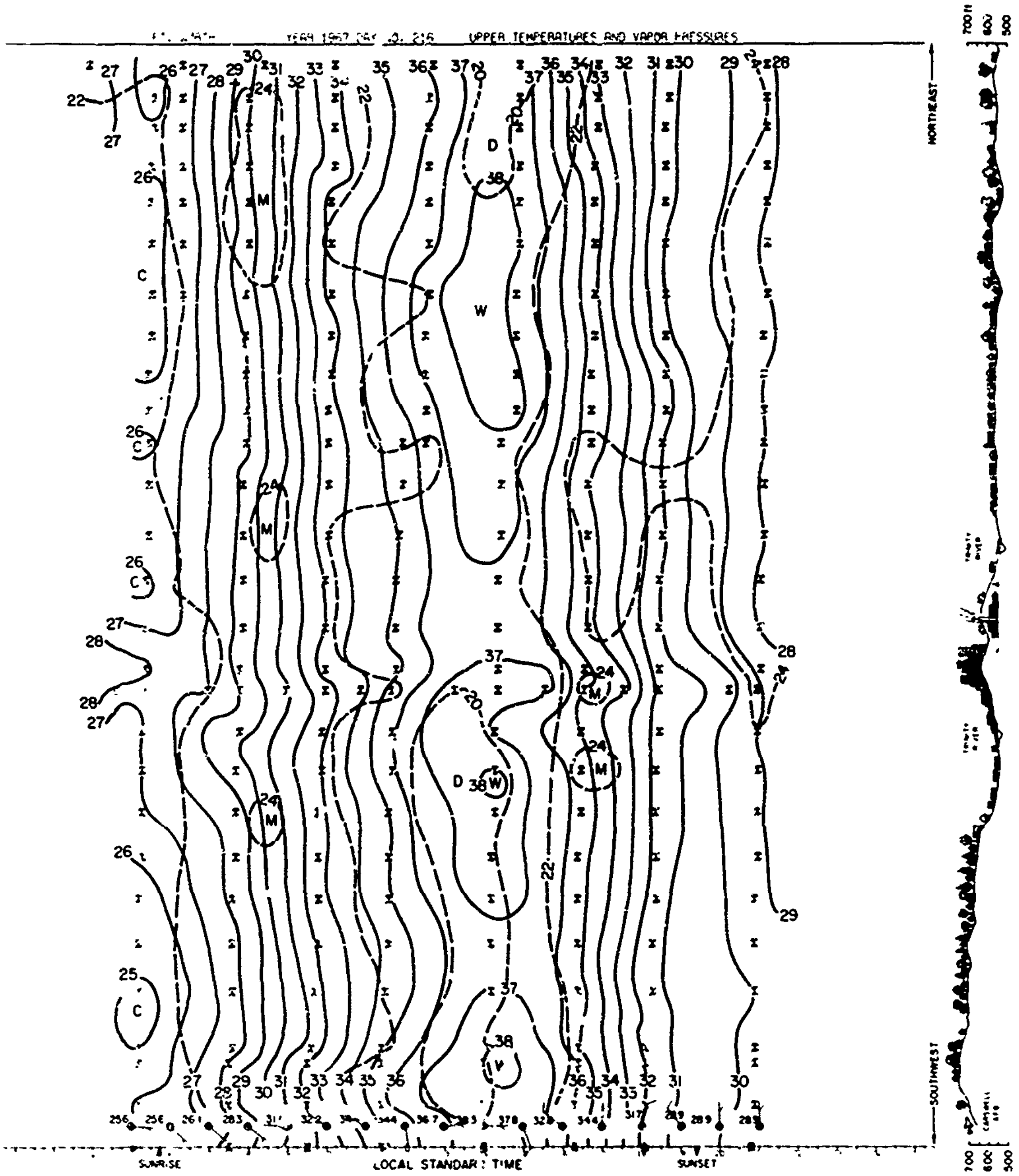

FIG. 12 FT. WORTH HORIZONTAL TIME SECTION, AUGUST 4, 1967, SW-NE

center is not located over the center of town but is displaced to the east at about 1400. By 1500 it is more or less centered over the city, but the whole pattern has begun to be distorted by the temperature gradients associated with the front.

In the afternoon and evening the low area around Pt. 54 on the southwest-northeast cross section cools only slightly more than it usually does, but the center of town cools much faster than usual with the passage of the front. As a result the very pronounced horizontal temperature gradients do not develop.

The Ft. Worth temperature cross sections from August 4, 1967, are shown in Figs. 11 and 12. The northwest-southeast cross section shows the familiar features which we found in the typical Dallas cross section. There is the pronounced heat-island in the center of town at the time of minimum temperature. The center of the city is cooler than the commercial areas on either side at the time of maximum temperature. The southwest-northeast cross section shows the nighttime heat-island, but the relatively cool area is displaced to the northeast and outside the heavily built-up area. This same phenomenon is detectable in the analyses of the other two days for which we have data in Ft. Worth, so it does not seem to be associated with the frontal passage. The cool temperatures northeast of the center of the city are in area of high freeway ramps which pass over some large open grassy areas near the Trinity River. It is not surprising that such an area is cooler than the downtown center. As we go farther to the northeast and into a commercial area the temperature rises again.

The front seems to have passed through Ft. Worth somewhat more regularly than it did through Dallas. At least, there do not seem to be the downtown temperature oscillations in Ft. Worth that were observed in Dallas.

Except for the rapid cooling following the frontal passage, this day appears much like the other two days in Ft. Worth. There were no apparent differences between Dallas and Ft. Worth which could be attributed

to their differences in size. However, differences were seen which can be accounted for by differences in morphology such as the above noted displacement of the cooler air outside the center of the downtown area.

b. Humidity

Fort Worth exhibits the typical diurnal humidity cycle on this day. Maximum humidities are reached around 0800 to 0900. Minimum humidities are reached about the time of maximum temperature. The humidity rises quickly in the late afternoon and changes little in the early evening.

In Dallas, the morning hours follow the expected pattern, with maximum humidities around 0900, but the presence of the front in the area distorts things somewhat. There was a shift from southerly to northerly winds at about 0900. With the arrival of the drier air from the north, the humidity dropped more rapidly than usual. The wind switched to the south again after noon and there was a rise in humidity until about 1400 to 1500. The air behind the front finally became established in the area and with it the temperatures and humidities dropped again.

As in the case with the temperatures, the humidity effects accompanying the frontal passage were apparently most strongly felt in the downtown Dallas area. In general, the humidity oscillations, connected with the wind direction changes, were most pronounced in the downtown area. It is not clear why this should be so, nor is it clear why Ft. Worth did not exhibit similar humidity variations. The wind direction in Ft. Worth underwent approximately the same variations as in Dallas.

D. Discussion

1. Temperature

The examples which we compiled for Dallas have presented a surprisingly organized picture of urban temperature features. The nighttime heat-island was expected. Virtually every study of urban temperature fields mentions

this feature. No such consensus existed for daytime effects. Yet when we look at the Dallas results the same features appear quite consistently. Furthermore, the Ft. Worth analyses exhibit the same features again, with one easily explainable change in pattern.

From the analyses it appears that the warmest areas of the city in the daytime are those with densely packed buildings of medium height. The downtown area with its very tall buildings is not quite so warm. Residential areas and areas with much vegetation are cooler still. A rather surprising fact is that these patterns are not distorted more than they are by other phenomena. As we have shown, these features are discernible even during a frontal passage. Changes in cloud cover, wind direction, and other factors do not generally obscure the general features we have described.

One of the most pronounced features of these analyses is the nightly cooling in some of the wooded and grassy hollow areas. The rapid collection of cool air in these areas in the late afternoon and early evening is worth noting. Temperature measurements made in such an area could be quite misleading if we attempted to apply them to other areas. It points out the importance of instrument location in determining how representative the measurements will be. It is also interesting to note that these temperatures differ most from the surroundings in the hours just before midnight, not at the time of minimum temperature. One further comment should be made about these cool pockets and that is that they are strongly affected by other factors, unlike some of the daytime temperature patterns. The frontal passage prevented the formation of a strong cool pocket, and individual cases show that cloudiness usually weakens the strength of these features.

At night, the heavily built-up center of town is the warmest area. This is in agreement with virtually all other studies of urban effects. In a later section, the magnitude of these effects will be discussed. For now, it is sufficient to note that the effects found in Dallas and Ft. Worth are in quite good agreement with observations made in other cities.

2. Humidity

For the temperature variations which were observed during the field program in Dallas, it was sufficient to show a few examples. The temperature fields exhibited regular features which occurred day after day. Magnitudes changed somewhat, but usually there were certain recognizable patterns which reoccurred throughout the series. When a typical humidity pattern is discussed, it represents a subjective evaluation of a wide variety of cases. As has been evident in the three cases just discussed, any given day may be typical in the morning and atypical in the afternoon, or visa-versa.

Probably, the reason for the wide variations in humidity cycle lies in the precarious balance between the two processes which appear to control low-level water vapor accumulations. These two competitors are the absorption-desorption rate of water vapor from the surface and the rate at which it is mixed to higher levels. In summertime Dallas it appears that the typical diurnal humidity cycle can largely be explained in terms of the diurnal cycle of mixing and convection. At night the air is stably stratified by the cooling from below, so there is little mixing of water vapor from the surface to higher levels. As a result, the humidity tends to rise through the night as water vapor accumulated in the lower layers. This continues until after sunrise when the ground heats, the air becomes less stable, and water vapor is mixed to higher levels, thereby lowering the humidity near the surface. When the ground begins to cool again, it brings with it increased stability, decreased vertical mixing, and the onset of a new cycle.

That is the typical summertime Dallas humidity cycle, but it can be altered substantially by rather small changes in vertical mixing or ground moisture. Too much cooling at night causes dew formation, removal of moisture from the atmosphere, and decreasing humidity instead of increasing humidity. Many of the cases show the humidity remaining virtually unchanged for hours. This indicates a near balance between the rate at which water vapor is put into the air and the rate at which it is mixed to higher levels. If the moisture content of the ground or vegetation were

increased slightly, it would tip the balance toward increasing humidity. An increase in convection or turbulent activity might reverse the situation. From day to day dominance shifts from one process to the other and the resulting humidity cycles change too.

The limited moisture sources in the city increase the likelihood that the city will have the same or lower absolute humidity in the daytime than the surroundings. The observations in Dallas bear this out. In virtually all cases the daytime downtown humidity is about the same as the environs or somewhat lower.

Chandler (1967) has suggested that nightime absolute humidities could be greater in the city than in the countryside if water vapor is removed in the country by dew formation but not in the city because of its higher temperatures. Whether this mechanism was definitely operating in Dallas is uncertain. The likelihood of the city being more moist than the countryside in the morning, at the time of maximum humidity, was about the same as the likelihood of it being less moist. Thus it is possible that rural dew formation reduced humidities to below the city values on some occasions.

In general, the differences in absolute humidity between one part of the area and another were less than about 2 mb (except in the immediate vicinity of the lake) at any given time. For a temperature of 35°C, this corresponds to a change in relative humidity of less than 4%. For a temperature of 25°C, a 2-mb change in vapor pressure corresponds to a change in relative humidity of about 6%.

III APPLICATIONS

A. Daytime Urban-Rural Temperature Differences

1. Background

A study of the data collected on this program, as well as data from other sources, indicates that differences between city and rural temperatures are generally small in the daytime. The low correlations between meteorological factors and daytime urban-rural temperature differences found by Chandler (1965) and Sundborg (1951) lead to the conclusion that these relationships are too tenuous to be useful, or at least that the extra effort required to incorporate many meteorological parameters into an elaborate specification scheme is very likely to be unjustified by improvements in the results.

Most of the available summaries of urban-rural daytime temperature differences show them to be small and relatively consistent. For example, the temperature measured at an urban London location is usually about 0.6°C warmer than that observed at a nearby rural site, and more than 95% of the time the value is within 2°C of this mode (Chandler, 1965, p. 150). Landsberg (1956) gives some data for Lincoln, Nebraska, and Cleveland, Ohio. For these two cities, city and airport temperatures have been compared. On a year-round basis the two temperatures are most frequently the same at Lincoln; in the summer the airport tends to be about 0.6°C warmer. More than 95% of the urban-rural temperature differences at Lincoln are within 2°C of 0. In Cleveland, the presence of a summer breeze from Lake Erie complicates the picture. The winter observations show that the city is most frequently about 0.6°C warmer than the airport and about 95% of the cases fall within 2°C of this value. The most common occurrence is for the city and airport maximum temperatures to be the same in the summer, but the distribution is very skewed toward those cases where the city is cooler than the airport. Landsberg says this arises because the city is often cooled by lake breezes in the summer, while

penetration of these breezes to the airport, which is farther from the lake, is less common and less effective. Thus Cleveland in the summer represents a special case and serves to remind us that our objective methods should be subjectively evaluated for individual cases.

Most of the data cited by Kratzer (1956) indicate that city maximum temperatures are about the same as rural maximum temperatures, although there is a slight tendency for the city to be warmer. Other examples of similar findings include Parry (1956) for Reading, England, Frederick (1964) for Washington, D.C., and Mitchell (1961) for New Haven, Connecticut.

The fact that temperature varies little between the city and its suburbs and that it is only slightly correlated with other factors suggests a simple correction based on some mean value for the difference between city and rural temperatures. This is the approach which has been adopted in the following section.

2. Average Urban-Rural Maximum-Temperature Differences

The data collected on this program appear to be the largest source of general daytime temperature distributions in urban areas. Other studies have generally compared one city station with one rural station, and without personal knowledge of the sites and exposures involved we cannot be confident that these temperatures typify the regions they are supposed to represent or that they are comparable to other studies. For this reason we have chosen to work with a set of data which seems to be reasonably compatible. All the data included were obtained from surveys of a city, usually by automobile, and most were obtained on this program with the same instrumentation.

Table I gives the sources of the data used in this study of daytime temperature differences. In each case, the warmest temperature near the center of town was used as the city temperature. As we have seen in Dallas, this warmest spot is not always in the center of the downtown area but is usually just outside this district. The rural temperature was chosen as that which appeared typical of he environs. To some extent this was a subjective average of the observed temperatures on

Table I

SOURCES OF URBAN DAYTIME TEMPERATURE DATA

City	No. of Cases	Reference
Dallas	20	This program
Albuquerque	12	This program
San Jose	12	This program
New Orleans	10	This program
Ft. Worth	4	This program
Minneapolis	3	Stanford U. (1953a, 1953d)
Winnipeg	3	Stanford U. (1953c)
Denton	2	This program
London	1	Chandler (1965)

the outskirts and in rural-type areas--not the lowest temperature in the field. This was done to avoid emphasizing some unusual or special feature of the area. For New Orleans (see Ludwig, 1967), the park areas about a mile from Lake Ponchartrain were chosen to typify rural conditions. In San Jose, the temperatures of the orchard areas to the north and to the southeast were generally averaged for the rural estimate; this was done to minimize the effects of the San Francisco Bay on the temperature field. In Albuquerque temperatures at the highest elevations of the city were generally avoided in favor of those in rural areas within about 125 meters of the elevation of the downtown center.

The differences between the city and rural temperatures were listed to the nearest half-degree Centigrade. The average city-country temperature difference and the standard deviation of the sample were calculated. On the average the city was 1.2°C warmer than the country. The sample standard deviation was about 1°C.

This sample has about the same standard deviation as have several of the other studies we have mentioned, but the average difference is somewhat higher. This probably reflects several factors. The city

temperature used in other studies may not have been taken at the warmest location of the urban center. For example, if the temperature in the center of downtown Dallas had been used, it would have been slightly less than the warmest temperature in the region. The rural stations chosen for the studies cited earlier may not have been as typical of the rural environment as the averages used here. In some of the cases cited, airport temperatures were used to represent the country, but the lack of trees and the presence of large areas of cement or macadam would make such temperatures warmer than a grassy or forested rural region; this in turn would result in smaller urban-rural temperature differences.

There does not appear to be a pronounced relation between city size and the daytime urban-rural temperature difference. The two cases available for Denton, Texas, the smallest town for which we have data, do not show any appreciable difference between maximum temperatures observed at the town's center and those observed at the edge of town, and it seems reasonable that a town as small as Denton would not have much daytime effect. However, for the larger cities in the study, the effect is about 1°C and does not seem to be a function of size.

As will be shown in the next section, the difference between urban and rural nighttime temperatures can be estimated to within about 2°C on the basis of a single meteorological parameter. The mean value for daytime city-country differences has about the same accuracy; in more than 90% of the cases the mean is within 2°C of the observed. Therefore, estimates of temperatures in the warmest part of a city can be improved by adding 1°C to a temperature measured in a rural area or a large park. For airport temperatures 0.5°C would probably be a better correction. Normally, in the daytime the warmest parts of a city seem to be the areas of densely packed three- to five-story buildings and parking lots. Areas of many taller buildings appear to have cooler daytime temperatures, more or less comparable to the airport, at least at street level.

The suggestions given above for modifying observed temperatures to give values suitable for built-up areas should not be applied indiscriminately. As the earlier cited case of Cleveland has shown, large-scale

geographical features can have a much greater effect than urban morphology. Cities near large bodies of water or with very large elevation changes should probably be considered individually. Most of the data studied on this program has been for cities of relatively flat topography and with smaller lake or sea breeze effects than might be found along the coast or the Great Lakes.

B. Nighttime Temperature Differences

1. Background

In attempting to relate the magnitude of urban-rural temperature difference to some other factor, there are at least two possible approaches which can be taken. If the primary purpose is to explain the differences, then we should investigate the parameters which are believed to cause them. However, if we are principally interested in discovering a useful relationship which will allow the specification of the differences with the greatest accuracy, then we might settle for a parameter which is influenced by the same parameters which affect urban-rural temperature differences. For our purposes, the latter approach has been pursued.

In a report by the Stanford Aerosol Laboratory (1953a) it was commented that there was a relationship between lapse rate and the urban-rural temperature difference which might have possible general applications. Although there has been no further mention of this relationship in the available declassified reports of this group, it is immediately apparent that the rate of change of temperature with height is an excellent candidate for predictor of heat-island effects.

Qualitatively, the relationship between lapse rate and heat-island strength develops from the following type of argument. At street level in a city, not much sky is visible and the buildings limit the wind and turbulent mixing. Consequently, the radiative cooling processes will not depend very much on sky conditions, and the transfer of heat from the surface by turbulent mixing will be relatively unaffected by wind speed. From this, we can infer that nocturnal cooling in the city is nearly independent

of meteorological conditions, and this in turn implies that differences in heat-island strength depend most strongly on the differences in rural cooling.

The lapse rate in the lowest levels is directly proportional to the difference between the surface temperature and the temperature at some higher level. As we go up there is a rapid decrease in the effects of surface conditions on the air temperature. So the lapse rate in the lowest layers depends primarily on the variation of surface temperature. If we consider only lapse rates measured outside the city, then both the magnitude of the heat-island effect and the lapse rate are largely determined by the rural surface temperature.

Other factors are certainly involved. These include the prevailing lapse rate and the urban-rural temperature difference at the onset of cooling, advection processes, and large-scale weather systems. The daytime urban-rural temperature difference is usually small and does not vary much from day to day. Afternoon lapse rates in the lowest layers tend to approach a constant value (a decrease of about 0.01°C per meter of height) because of turbulent mixing and adiabatic processes. As has already been shown, advection effects should generally be minimal in the city and the rural wind will affect both lapse rate and the low-level rural temperature. The effects of synoptic-scale weather systems should be limited to those times when there is a change of air mass during the cooling period. Such occasions should be relatively rare.

We have shown, at least qualitatively, that lapse rate and the urban-rural temperature difference should be closely related and the relationship should be approximately linear. At this point, it is not clear whether differences among cities should affect the nature of this relationship.

2. Relationship Between Lapse Rate and Urban-Rural Temperature Difference

a. Data

Fortunately, we have been able to find a reasonably large number of cases to test the relationships discussed above. The data sources are summarized in Table II. Most of the heat-island magnitudes were determined

Table II

SOURCES OF NIGHTTIME TEMPERATURE DATA

City	No. of Cases	Type of Sounding	Radiosonde Location	Distance From City (km)	References
Minneapolis	24	Wiresonde	--	--	Stanford U. (1953a, b, d)
Minneapolis	4	Radiosonde	St. Cloud	100	
Dallas	18	Radiosonde	Ft. Worth	25	This program, U.S. Weather Bur. data
Winnipeg	3	Wiresonde	--	--	Stanford U. (1953c)
London	8	Radiosonde	Crawley	45	Chandler (1965), U.S. Weather Bur. data
St. Louis	4	Radiosonde	Columbia	190	Stanford U. (1953a)
Ft. Worth	3	Radiosonde	Ft. Worth	25	This program, U.S. Weather Bur. data
Albuquerque	2	Radiosonde	Albuquerque	--	This program, U.S. Weather Bur. data
San Jose	2	Radiosonde	Oakland	50	This program, U.S. Weather Bur. data
Leicester	2	Radiosonde	Hemsby	185	Chandler (1967)
Palo Alto	1	Wiresonde	--	--	Duckworth and Sandberg (1954)
San Francisco	1	Wiresonde	--	--	Duckworth and Sandberg (1954)
Denton	1	Radiosonde	Ft. Worth	45	This program, U.S. Weather Bur. data

from maps of the temperature field for the various cities involved. For the Texas cities and for San Jose, the heat-island magnitudes were determined from the early morning portions of the time sections presented in Appendix B. As in the case with daytime effects, a temperature typical of the environs was subtracted from the temperature in the warmest part of the central city. Particularly cold pockets which often form in low lying areas were generally avoided. For Leicester, U.K., the magnitude of the heat-island was stated in the reference. In a few cases for London the data came from automobile traverses across the city, and the difference was taken between the city temperature and a temperature typical of the outskirts. The other London cases have been based on the field of minimum temperatures.

The lapse rates for most cases have come from the radiosonde soundings taken nearest the city. The locations of the radiosonde stations and their approximate distances from the city are given in the table. The radiosonde data for England were collected about an hour before midnight local time. The radiosonde information collected on our program was taken an hour or two before sunrise. The lapse rate was determined from the temperatures at the surface and the first reported level above the surface. These lapse rates have been calculated in terms of rate of change of temperature with pressure in units of degrees Centigrade per millibar. Because pressure decreases with height, the lapse rate can be expressed in these terms. When this parameter has a negative value it indicates an increase of temperature with height.

For much of the data reported by Stanford University and the Parsons Company (1953, a,b,c,d) and by Duckworth and Sandberg (1954), wiresonde measurements were available. These measurements were made using a tethered balloon in the environs of the cities. The measurements were usually taken within about an hour of the heat-island data. In most of these cases the lapse rate was determined from the difference between the surface temperature and the temperature at 300 feet. In some cases the sounding did not reach 300 feet and the temperature at the top of the

sounding was used. These lapse rates were then converted to the same units used for the radiosonde data.

The wiresonde data is probably superior to the radiosonde data for several reasons. Foremost is the nearness in time and space to the city temperature fields. Table II shows that some of the radiosonde data were taken nearly 200 km from the city being studied. There are also differences of several hours in time between radiosonde measurements and some temperature fields. Another factor is the difference in spatial resolution between the two types of instrument. The reported radiosonde data do not resolve small features in the vertical temperature gradient. With an ascent rate of about 5 meters per second and a lag time of about 3 1/2 seconds (Middleton and Spilhaus, 1953), the spatial resolution is about 15 to 20 meters. This means that shallow temperature inversions may not be detected or may be appreciably smoothed. The wiresonde does very well at measuring this low-level temperature structure. In spite of the radiosonde's shortcomings, the results show no obvious differences between the wiresonde and radiosonde data.

b. Results

The data relating urban-rural temperature differences and lapse rates are plotted in Fig. 13. The solid line represents the best fit of the data. The equation for this line, covering data from all the cities is:

$$\Delta T = 1.85 - 7.4\gamma$$

where ΔT is the city temperature minus the rural temperature in degrees Centigrade and γ is the rate of change of temperature with pressure in degrees Centigrade per millibar. The correlation coefficient between these two parameters is -0.79. The root mean square error (RMSE) for the specification of ΔT using the equation is 1.2°C. The two dashed lines in Fig. 13 show the bounds of the area within ±2.4°C (2 RMSE) of the line defined by the equation. This region contains 93% of the points indicating that the equation could reasonably be expected to define the magnitude of the

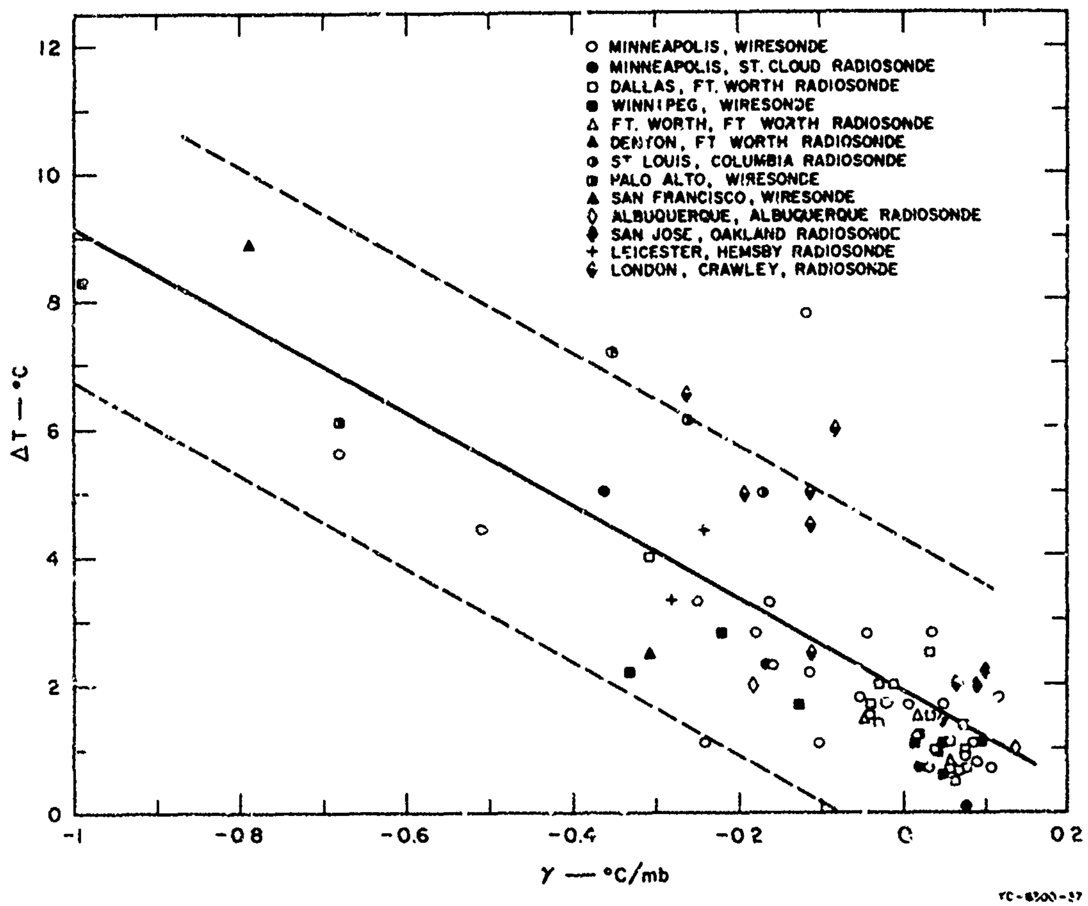

FIG. 13 URBAN-RURAL TEMPERATURE DIFFERENCES AS A FUNCTION OF LAPSE RATE IN THE LOWEST LAYERS—ALL CASES

heat-island within about ±2.5°C if lapse rate data are available within a reasonable distance of the city.

Although one would expect a close relationship between heat-island strength and lapse rate, it is surprising that this one parameter correlated more closely with the heat-island than do the multiple parameters used by Chandler (1965) or Sundborg (1951). They found multiple correlation coefficients for London and Uppsala of about 0.6.

It is evident from Fig. 13, that most of the errant points are from either London or St. Louis.* If these two cities are removed from the calculations, the correlation is then -0.85 and the RMSE is reduced to 1.0°C.

An effort has been made to discover a reason for the pronounced difference between the points for London and St. Louis and those for the other cities. As part of this search, Table III was prepared. This table lists the cities and their approximate populations at the time the measurements were made. From the table we can see that London and St. Louis are the two most populous cities in the list. Also, almost all the points for the five smallest cities fall below the regression line. This tends to support the contention of Duckworth and Sandberg (1953) that there is a relationship between population and the magnitude of the heat-island. Such a relationship certainly seems reasonable.

The cities listed in Table III were divided into three groups; (1) the smallest five, (2) the next five in size, and (3) the two largest cities. Regression equations were calculated for the data from each group. Fig. 14 shows the lines and the points for which they have been drawn.

*There is one Minneapolis point which is very far above the line. The source (Stanford U., Parsons Company, 1953a) was rechecked and there is no apparent reason for doubting the validity of the point so it has been retained.

Table III

CITY POPULATIONS AND AREAS

City	Population (thousands)		City Area (sq. miles)	Year of Data
	City	Metropolitan Area		
London	3348	8346	722	1951
St. Louis	857	2268	61	1950 (1960, Metro. Pop.)
Dallas	790	1280	254	1965 (1960, Area)
San Francisco	784	--	45	1950
Minneapolis	522	1107	57	1950
Ft. Worth	360	540	138	1965 (1960, Area)
San Jose	359	650	56	1965 (1960, Area)
Leicester	270	--	--	1957
Winnipeg	236	354	--	1951
Albuquerque	201	317	58	1965 (1960, Area)
Denton	36	--	--	1965
Palo Alto	33	--	9	1950

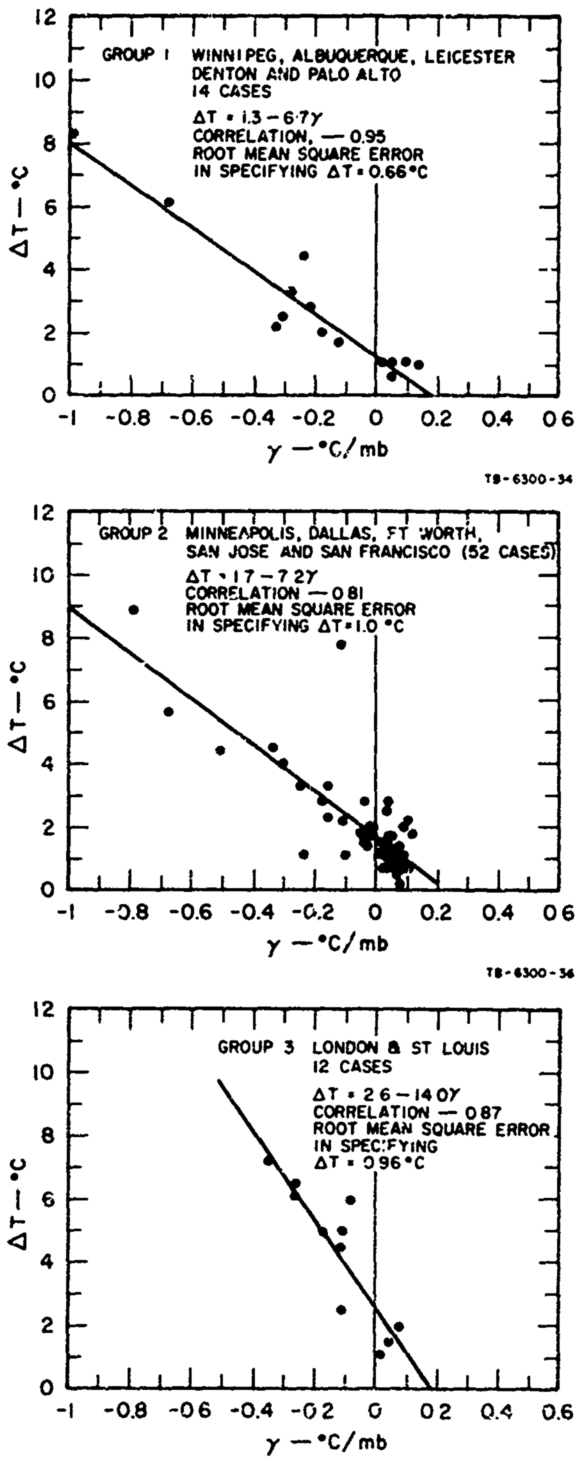

FIG. 14 URBAN–RURAL TEMPERATURE DIFFERENCES AS A FUNCTION OF LAPSE RATE IN THE LOWEST LAYERS—BY CITY SIZE

The equations for the three groups of cities appear to apply to the following approximate size ranges, using the population of the metropolitan area as an index:

Group (1)	Cities $< 500,000$
Group (2)	Cities between 500,000 and 2 million
Group (3)	Cities $>$ 2 million

These categories are, of course, very approximate. The equations appropriate to the three size groups are:

Group (1) $\Delta T = 1.3 - 6.78\gamma$

Group (2) $\Delta T = 1.7 - 7.24\gamma$

Group (3) $\Delta T = 2.6 - 14.8\gamma$

The correlation coefficients are (1) -0.95, (2) -0.80, and (3) -0.87. The root mean square errors in the specification of ΔT are (1) $\pm 0.66^{\circ}C$, (2) $\pm 1.0^{\circ}C$, and (3) $\pm 0.96^{\circ}C$.

3. Remarks

It has been shown that the magnitudes of urban heat-islands and of lapse rates in the lowest layers are very highly correlated. To avoid misunderstanding, it should be reemphasized that this relationship is not one of cause and effect. The relationship is more that of "effect and effect." Both effects, the heat-island and the low-level lapse rate, arise from the same causes. These causes are predominately radiative cooling of the surface and turbulent heat transfer at the lowest levels. While this is not very satisfying as a physical explanation of either phenomenon, it is a very useful relationship for the purposes at hand.

C. Suggested Corrections for Urban Effects

1. Temperature

With the availability of machines for processing data, it is quite feasible to use the equations given in the preceding section to adjust reported airport temperatures so that they more nearly coincide with the temperatures found in the downtown area. The maximum temperature correction

is simply a matter of adding a constant in most cases. To correct the airport maximum temperature to the 2-meter temperature in the area of three- or four-story buildings surrounding the central core of the city, 0.5°C should be added. It appears that daytime airport temperatures are fairly representative of central section temperatures if the central section is one of tall buildings.

Existing data indicate that the procedures outlined above are somewhat better than using the airport temperature unadjusted. The few studies that are available indicate that the warmer area temperatures of a city are specified within ±2°C in greater than 90% of the cases, using the above procedure. However, the correction should not be applied indiscriminately, because many locations are subject to special influences.

Among the more common special situations which affect daytime differences between city and airport temperatures are those caused by sea or lake breezes. If the airport is farther from a large body of water than the city, airport temperatures may often be warmer than the city. If it is closer, the airport may be anomalously cooler.

The differences between airport and city temperatures are more pronounced at night than during the day. The equation for the appropriate city size can be used with lapse rate information from the nearest radiosonde station. Over most of the United States radiosonde launchings occur in the early morning hours. The nominal time for one of the two usual radiosonde launchings is 1200 Greenwich Standard Time. This corresponds to 0400 Pacific Standard Time and 0700 Eastern Standard Time. However, the balloons are usually launched about an hour before their nominal time. Thus, the soundings are made from a few hours before sunrise to shortly after, depending on the time zone and the season. Lapse rate measurements made after sunrise will be likely to result in an underestimate of the heat-island strength at the time of minimum temperature. Nevertheless, estimates should generally be more accurate than the unadjusted airport temperature.

To determine lapse rates the following relation should be used:

$$\gamma = (T_o - T_1)/(P_o - P_1)$$

where T_o and P_o are, respectively, the reported temperature and pressure at the surface, and T_1 and P_1 are the temperature and pressure at the first level reported above the surface. The temperature units should be in degrees Centigrade and pressure units should be millibars if the equations given earlier are to be used. The nearest radiosonde station to the city of interest should be used. Radiosonde sites near large bodies of water should be avoided if possible because large bodies of water will alter the night inversion forming processes. It is not known how close the radiosonde site must be to be effective in specifying heat-island effects, but some of the stations used in this study were nearly 200 km from the corresponding urban areas.

Admittedly there could have been more data used to develop regression equations, particularly the equation for very large cities. However, the connection between lapse rate and heat-island effects is so strong that these equations should result in substantial improvements over unadjusted airport data.

2. Humidity

Very little information is available on the variation of urban humidities. The data gathered on this program are probably more complete than those from any other source. On the basis of what we have learned from this study, it is recommended that absolute humidities as measured at the airport be used for design purposes.

In Dallas, absolute humidities generally varied through the area by about the equivalent of 5% or less in relative humidity (except in the immediate vicinity of the lake). For high temperatures (> 30°C), this is comparable to the error that would result from a 1°F wet-bulb

temperature error in the psychrometric determination of humidity (Middleton and Spielhaus, 1953). Inasmuch as expected variations of humidity in an area are apt to be comparable to errors of measurement, it does not seem unreasonable to consider ignoring the urban variability in humidity.

Most studies agree that daytime urban absolute humidities are probably less than rural humidities. The work in Dallas has confirmed this. By using airport values of humidity, we are then likely to obtain a conservative estimate; that is, we are more apt to overestimate the humidity and hence the magnitude of the potential problem of shelter ventilation. The rather sparse evidence suggests that downtown vapor pressures may average about a half-millibar less than rural values in the daytime, but we feel that it would be better to play it somewhat safe than to make corrections on this uncertain basis.

Even less is known about the night and morning humidities. Again our studies have led us to believe that the urban variability is small. In the case of Dallas in the summer, the city humidities in the morning are equally likely to be greater or less than the surrounding humidities. This supports the contention that it is best to use uncorrected airport values of absolute humidity.

In all the foregoing discussion we have been talking about absolute humidity. We do not feel that there is adequate basis or reason to correct airport values of this parameter. However, we have already shown that there are reasonable adjustments which can be made to airport temperatures to make them more representative of downtown temperatures. Changing temperature without changing absolute humidity will change relative humidity. Therefore, relative humidities should be adjusted in conformance with the temperature adjustments.

IV A SUGGESTED PROGRAM FOR IMPROVING THE RELIABILITY OF HEAT-ISLAND SPECIFICATION

That there is a very strong correlation between low-level lapse rates and the night urban heat-island is beyond question. The data given in the preceding section prove this. The remaining question concerns the effects on this relationship of city size, morphology, and geography. It appears that very large metropolitan areas have correspondingly larger heat-island effects than smaller cities. However, the quantitative statement of this effect is based on data from only two cities. It would be desirable if more data could be accumulated, particularly for the very large cities.

The collection of such data would not require as elaborate a program as the one used to collect data in Dallas. Now that a useful relationship has been established it would suffice to have minimum and maximum temperatures recorded at 6 to 12 key locations in and around several cities. The cities could be chosen to represent a variety of types. Two or three thermometers would be located in the downtown area and several in rural locations. These measurements combined with official Weather Bureau measurements would suffice to define urban and rural conditions.

The instruments and materials necessary for shelter construction should cost about \$25 to \$50 per location. Thus the initial cost of materials for such a program would be several hundred dollars per city. The instruments could be monitored by Civil Defense personnel in the chosen cities. Locations could probably be chosen to be convenient to the local Office of Civil Defense or to the residences of personnel in the office.

In some cities, maximum and minimum temperatures have been recorded at several locations for many years as part of the Weather Bureau's cooperative observer program. These locations would be used in the program wherever possible. By using these cooperative observing

stations and Civil Defense personnel, it should be possible to collect a large amount of data with a minimum amount of labor cost.

The cities should be chosen to provide a variety of sizes and geographical settings. In addition, it would be useful if a radiosonde site were reasonably close. Another important factor might very well be the number and location of established climatological observing stations.

The largest part of the effort in such a program would be the establishment of the network and the interpretation of the results. It would be mandatory that the data be put into a format suitable for computer processing. The establishment of the network would require considerable time. First, the cities would have to be selected. and then the sites within each city. The sites should be meteorologically representative of the types of areas to be compared yet satisfy a number of practical considerations. Suitable downtown sites are likely to be difficult to find.

Although such a program presents some difficulties, the amount of information which could be collected should more than justify the effort. About a year of measurements in a dozen cities would increase the amount of data available by about fiftyfold. This would provide a much greater data base for the regression equations presented here, especially with respect to the dependence on city size. The program would considerably improve our knowledge and understanding of urban climatological effects.

Appendix A

DATA COLLECTION PROGRAM

Appendix A

DATA COLLECTION PROGRAM

A number of routine functions must be performed in data collection programs of the size of this one. A detailed knowledge of the operations is not generally essential to understanding the results of the program but can often be quite useful to others planning similar work or to those who wish to examine the results more closely. In this Appendix, some of the peripheral details of site selection and instrumentation are presented.

A. Criteria for the Selection of Sites

Before making the final selection of an area to be used for the temperature measurement program, various regions were considered and evaluated according to a certain criteria. It was especially important that the area be as free as possible of temperature-influencing topographical features. It was desirable to have, in the same general area, cities of several sizes with populations from a few thousand to about a million. Another factor which was considered in the site selection process was the probability of rain. Past experience had shown that rain tended to obscure temperature and humidity effects caused by urban features. Other climatological characteristics considered were the average maximum temperature and the frequency of occurrence of high temperatures. Urban effects on temperature distribution during hot weather are of more interest in this program than are the cooler weather effects. For this reason, cities in the northern tier of states were not considered. Finally, the size of the downtown center, the symmetry of the metropolitan area, and the ease of moving about by auto within the city were considered.

On the basis of these last factors, Kansas City, Missouri, and Omaha, Nebraska, were eliminated early in the selection process. Topographic and road maps of these areas indicated that it would be difficult to cross the rivers bisecting the metropolitan areas. Three candidate regions were

left: Dallas-Ft. Worth, Texas; Indianapolis-Anderson, Indiana; and Columbus-Springfield, Ohio. Topographic maps, road maps, climatological data, and census information were obtained for these areas. This information is summarized in Table A-1.

The table shows that the three areas are about equally flat; the routes which would cover the cities have an elevation range of about 200 feet and are about 50 miles long for the main urban center. None of the three areas has major bodies of water nearby. Dallas is the largest urban center considered, but the others are comparable. Ft. Worth has a population about half that of Dallas, and the populations of Springfield and Anderson are about one-seventh the populations of the nearby major cities.

The likelihood of rain in July and August in Indianapolis or Columbus is almost twice that of Dallas. The average cloud cover is less in Dallas than in the other two cities. The average temperature in Dallas is about 6° or $7^{\circ}C$ warmer than the average temperatures for the other areas. Furthermore, the probability that temperatures will exceed $32.2^{\circ}C$ ($90^{\circ}F$) is more than three times as great in the Dallas area as in the other cities considered.

The choice of Dallas as a test area was based primarily on climatological factors. Dallas is clearly superior, climatologically, for the study of hot-weather urban-temperature effects. In other respects such as topography, population, symmetry, and other nearby cities, Dallas was equal or nearly equal to the other areas considered.

Table A-1

GEOGRAPHIC INFORMATION ON THREE CANDIDATE TEST AREAS*

	Dallas-Ft. Worth			Columbus-Springfield			Indianapolis-Anderson		
	Dallas	Ft. Worth	Denton	Columbus	Springfield	London	Indianapolis	Anderson	Noblesville
Elevation (ft)									
High	610	695	700	900	1060		870		
Low	405	540	615	690	900		695		
Difference	205	155	85	210	160		175		
Approximate Route Length Needed to Cover Area (mi)	50	50	15	50	15		50		
Population (thousands),									
City	790	360		540	83	6	530	70	9
Metropolitan Area	1280	540	36	825	116		900	137	
Distance from Principal City (mi)		34	36		43	25		35	23
No. of Rains > 0.1"									
July	4		4	7	8	8	8	8	6
Aug.	3		3	6	5	5	6	6	6
No. of Rains > 0.5"									
July	1		1	3	2	3	4	3	2
Aug.	1		1	2	2	2	2	2	2
Avg. Precipitation (in.)									
July	1.7	1.7		4.2	3.7	4.3	5.1	3.9	4.2
Aug.	1.4	1.3		2.3	2.7	3.0	3.6	3.0	2.8
Avg. Cloud Cover (tenths)									
July	3.8	3.9		4.8			4.8		
Aug.	3.9	3.8		4.9			4.8		
Avg. Maximum Temp. (°C)									
July	36.0		36.1	30.4	30.8	29.5	29.8	30.3	
Aug.	36.2		37.0	29.9	30.3	28.7	29.4	29.8	
Avg. Minimum Temp. (°C)									
July	24.6		22.9	17.4	17.4	16.8	18.6	17.7	
Aug.	24.3		22.9	16.7	16.9	16.1	17.7	16.8	
No. of Days > 32.2°C									
July	28		28	10	12	6	8	9	
Aug.	28		30	8	8	6	7	7	

* The sources of the data used in this tabulation are listed in Section E of this Appendix.

B. Route Descriptions

1. Dallas, Texas

A topographic map of the Dallas area is shown in Fig. 1 of Section II; built-up areas are indicated by shading. The various numbered points along the route denote the locations where wet- and dry-bulb temperature readings were taken. An aerial view of downtown Dallas and its environs is shown in Fig. 2 of Section II.

Table A-II gives the locations of the points shown in Fig. 1, lists the elevations of the area (estimated from U.S. Geological Survey maps), and gives a brief description of the various segments of the route.

Table A-II

DALLAS ROUTE DESCRIPTION

Point No.	Intersection	Approximate Elevation (ft)	Description
1	Harry Hines--Mockingbird	450	
			Some large buildings with much open space between.
2	Harry Hines--Inwood	445	
3	Harry Hines--Lofland	450	Pt. 2 to Pt. 4 similar to section between Pt. 1 and Pt. 2, but with some warehousing and light industry NE of route.
4	Harry Hines--Kendal	450	
5	Harry Hines--Douglas	405	Some warehousing and large open areas SW of route; commercial buildings line NE side with residences behind.
6	Harry Hines--Oaklawn	410	
7	Harry Hines--Ivan	465	Large, lightly wooded spaces, two motels, and a freeway overpass under construction.
			Apartments, vacant lots, park, and motel.
8	Harry Hines--Payne	430	
9	Akard--Munger	440	3- and 4-story buildings at edge of downtown core.
10	Akard--Federal	445	Downtown core with many large, densely packed multistory buildings.
0	Akard--Commerce	430	
11	Akard--Marilla	440	
			Auditorium complex, warehouse, and some open space.

Table A-II (Continued)

Point No.	Intersection	Approximate Elevation (ft)	Description
12	Akard--Cadiz	445	Older area with warehousing, commercial buildings, a few large old houses, and some trees.
13	Akard--Powhattan	420	
14	Akard--McKee	430	
15	Lamar--Alma	430	Mixture of industrial and warehousing buildings with an occasional residence or wrecking yard; some trees.
16	Lamar--Forest	415	
17	Lamar--Lenway	410	
18	Lamar--Poplar	420	
19	Lamar--Hatcher	410	Residential with some large trees NE of route, commercial along SW side with large, open, lightly wooded areas behind.
20	Lamar--Haven	415	Same as Pt. 18 to Pt. 19, but commercial on NE side of street.
			Expressway and open space along E side of route, residential beyond; commercial along W side with Trinity River bottom lands beyond.
21	Lamar joins Central Expwy	410	Viaduct above wooded bottom lands of Trinity River; bridge well above level of surrounding terrain.
22	Central Expwy crosses Trinity River	420	
23	Central Expwy--Jaffee	420	Leaves bridge, then through commercial strip along route; residential and lightly wooded open spaces beyond.
24	Central Expwy--Bascom	420	Open country with some trees; some commercial and warehousing activities line route.
25	Central Expwy--on ramp from Illinois		
26	Central Expwy--Ledbetter	415	SE end of NW-SE cross-section line.
			First 1/2-mile through open fields, then residential with many trees and large open spaces.

Table A-II (Continued)

Point No.	Intersection	Approximate Elevation (ft)	Description
27	Ledbetter--Lancaster	430	
			Residential with many trees and large open spaces, some large wooded and grassy parks, a little commercial activity at roadside.
28	Ledbetter--U.S. Hwy 77	480	
			First 1/2-mile open with stone quarry to N, then 1/2-mile of open highway construction, then residential.
29	Ledbetter--Hampton	610	Pt. 29 has shopping center on NE corner and small airport off route to SW.
			Large grassy, wooded plots and residential areas with trees; commercial for last few blocks before Pt. 30.
30	Hampton--Illinois	605	
			First 1/4-mile mixed residential and open plots with trees, then 1/2-mile residential with trees, 3/4-mile residential behind commercial along route, remainder residential with trees.
31	Hampton--Davis	550	SW end of SW-NE cross-section line.
			First 1/4-mile residential with large lots and many trees, followed by golf course and park; last 2 blocks mixed commercial and residential.
32	Hampton--Ft. Worth	550	Commercial along route with residences and apartments behind to SE; open areas and turnpike behind to NW.
33	Ft. Worth--Vilbig	495	

Table A-II (Continued)

Point No.	Intersection	Approximate Elevation (ft)	Description
34	Ft. Worth--Edgefield	470	Route lined with commercial buildings; behind these are residences to NW and turnpike to SE.
35	Ft. Worth--Sylvan	430	
36	Ft. Worth--Haslett	430	
			Commercial area.
37	Commerce Viaduct--Beckley	440	
			Viaduct above Trinity River.
38	Commerce--Rock Island	430	
			Past some used car lots, then under highway.
39	Commerce--Railroad underpass	400	
			Under railroad and through small plaza at edge of central downtown area.
40	Commerce--Record	420	Downtown core with many closely spaced multistory buildings.
41	Commerce--Poydras	425	
0	Commerce--Akard	430	
42	Commerce--St. Paul	450	
43	Commerce--Central Expwy	460	Area of 1- to 4-story brick and masonry buildings intermixed with parking lots.
44	Commerce--Dove	465	
45	Commerce--Craodus	465	
46	Commerce--1st	465	
47	Exposition--Parry	460	

Table A-II (Continued)

Point No.	Intersection	Approximate Elevation (ft)	Description
			Passes State Fair Grounds with 2- or 3-story stucco or masonry buildings near route on SW side; residences behind buildings on NE side.
48	Grand--Haskell	460	
			Commercial along route, residential behind.
49	Grand-- St. Mary's	470	
			Automobile assembly plant SE side.
50	Grand--Wayne	505	Commercial along route, residential behind.
			Residential to NW, open grassy park to SE.
51	Grand--Tenison Pkwy	490	
			Wooded, grassy park area, rolling terrain. Some residences off route to NW.
52	Grand--Tenison Memorial Dr.	475	
53	Grand-- Coronado	485	Commercial along route; some residential off route to NW for first half and open areas for second half; open off route to SE.
54	Grand-- San Rafael	460	
			White Rock Lake to NW, large residences with large grassy, wooded lots to SE.
55	Grand-- Lawther	470	
			Large residences SE for first half, then smaller residences and commercial. Wooded park area NW along route with lake beyond.
56	Garland-- Timplemore	530	
57	Garland-- Old Gate	520	Commercial along route, residential off route to SE, park and lake off route to NW.
58	Garland-- Buckner	520	NE end of SW-NE cross-section line.
			First half open, grassy, wooded park; second half residential (with trees) along route, park, and lake off route to SW.
59	Buckner-- Northcliff	525	

Table A-II (Continued)

Point No.	Intersection	Approximate Elevation (ft)	Description
			Open grassy and wooded area, lake to SW.
60	Buckner--Northwest Hwy	470	
			First mile open grassy and wooded area; then 1/2-mile residential with smaller trees; 1/2-mile of commercial along route, open areas beyond; 1 mile of open area with scattered woods, some commercial buildings along road.
61	Northwest Hwy--Central Expwy	585	
			First 1/4-mile open S of route, shopping center N of route, then 3/4-mile residential apartments to S, cemetery to N; remainder residential with smaller trees S, 2- or 3-story apartments to N., some multi-story buildings; last 2 blocks commercial along route.
62	Northwest Hwy--Preston	580	
			2 blocks commercial S of route, remainder residential with large lots, trees and grassy areas.
63	Northwest Hwy--Midway	490	NW end of NW-SE cross-section line.
			1/2-mile heavily wooded residential, then residential with trees; last block commercial and apartments to W.
64	Bluff View--New Lemmon	505	
			Airport to NW; residential with open areas to E; last 3 blocks commercial along route.

Table A-11 (Concluded)

Point No.	Intersection	Approximate Elevation (ft)	Description
65	Mockingbird--Cedar Springs	475	
66	Love Field Parking Lot Entrance	465	Entrance to airport, runway areas on both sides, some commercial on NE side of route.
65	Mockingbird--Cedar Springs	475	
			2 blocks with airport to NW, remainder small industrial and warehousing.
1	Mockingbird--Harry Hines	450	

2. Ft. Worth, Texas

An aerial view of downtown Ft. Worth is shown in Fig. 4 of Section II. The topography and built-up areas are shown in Fig. 3. Table A-III gives information about the numbered points in Fig. 4 and the nature of the route between these points. The elevations were estimated from topographic maps.

Table A-III

FT. WORTH ROUTE DESCRIPTION

Point No.	Intersection	Approximate Elevation (ft)	Description
1	Interstate 820S--Texas 183	555	NE end of SW-NE cross-section line.
2	Interstate 820S--Dallas-Ft.Worth Tpk	640	
3	Interstate 820S--Lancaster	610	Generally open, lightly wooded; highway
4	Interstate 820S--Wilbarger	585	
5	Interstate 820S--Mansfield Hwy	600	SE end of NW-SE cross-section line.
6	Mansfield Hwy--Anglin	640	
7	Mansfield Hwy--Hartman	660	
8	Mansfield Hwy--Trentman	660	Some commercial along road, generally open NE of route and some residential to SW, increasing residential NE of route beginning about Pt. 9.
9	Mansfield Hwy--Dorman	640	
10	Mansfield Hwy--Trueland	660	
11	Mansfield--Pecos	690	
12	Mansfield--High Point	650	
13	Riverside--Rolling Hills	580	Large open areas SW of route, some commercial along route, some residential to NE.
14	Riverside--Berry	575	
15	Riverside--Colvin	590	
			Mixture of residential, commercial, and open plots along road; large open plots and residential off road.

Table A-III (Continued)

Point No.	Intersection	Approximate Elevation (ft)	Description
16	Riverside--Arlington	610	
17	Riverside--Morphy	595	
18	Riverside--Vickery	550	Commercial and residential along route, generally residential off route, railroad yards N of route for a few blocks before Pt. 20.
19	Vickery--Stella	570	
20	Vickery--U.S. 81	610	
			Industrial and warehousing.
21	Vickery--Main	630	
0	Throckmorton--7th	610	Downtown center with large, multi-story, closely spaced buildings.
22	Throckmorton--Weatherford	620	
			Leaving downtown center, cross viaduct.
23	Main--4th	540	
			Commercial, industrial, warehousing.
24	Main--8th	540	
			Commerical, industrial, warehousing.
25	Main--Northside	550	
26	Main--21st	560	
27	Main--25th	540	Commercial along street, residential off route to W, stockyards off route to E.
28	Main--29th	610	
29	Main--33rd	630	Commercial along route, residential off route.
30	Main--38th	650	
31	38th--Ross	650	Residential SE of route, Meacham Airfield NW.
32	Ross--33rd	650	NW end of NW-SE cross-section line.
			Residential with some open areas and many trees.

Table A-III (Continued)

Point No.	Intersection	Approximate Elevation (ft)	Description
33	Long--Jacksboro Hwy	615	
			Commercial along route, residential off.
34	Gen. Arnold--Skyacres	555	
			Residential and large open areas, Carswell Air Force Base NW of route.
35	Gen. Arnold--Texas and Pacific RR after Carswell AFB	660	SW end of SW-NE cross-section line.
36	Interstate 20--Ridglea	760	
			Highway through mostly open area.
37	Interstate 20--Guilford	740	
			Highway through residential area.
38	Camp Bowie--Horne	700	
39	Camp Bowie Neville	695	
40	Camp Bowie--Hulen	670	Mixed residential and commercial along route, residential with many trees off route.
41	Camp Bowie--Clover Lane	675	
42	Camp Bowie--Montgomery	635	
			Commercial along N side of route and residential off route, park and residential off route to S.
43	7th--Camp Bowie	545	
44	7th--Stayton	550	Commerical.
45	7th--Summit	580	
0	7th--Throckmorton	610	Downtown center with large, closely spaced, multistory buildings.
46	7th--Jones	595	

Table A-III (Concluded)

Point No.	Intersection	Approximate Elevation (ft)	Description
			Mostly over highway ramps at downtown edge, industrial area and railyards.
47	U.S. 377--Interstate 35	550	
			Highway ramp, much open grassy area.
48	U.S. 377--Belknap	540	
			Over Trinity River, then through commercial area; residential with trees off route to SE.
49	Belknap--Emma	560	Commercial along route, some residential just off route.
50	Belknap--Hudgins	560	
51	Belknap--Beach	560	
52	Belknap--Oakwood	560	Commercial along route, residential and large open areas off route.
53	Belknap--Fincher	560	
54	Belknap--Cosgrove	550	
55	U.S. 377--Texas 121	560	
56	Texas 121--Carson	560	
57	Texas 121--Texas 183	520	Mostly open area, some commercial along route.
58	Texas 183--Snow	550	
59	Texas 183--Vance	550	
60	Texas 183--Handley-Ederville	570	
1	Texas 183--Interstate 820S	555	NE end of SW-NE cross-section line.

3. Denton, Texas

Denton, Texas, is about 35 miles northwest of Dallas and on several occasions measurements were made there concurrently with those in Dallas. The route used, the topography, and the built-up areas are shown in Fig. A-1. The numbered points are identified and described in Table A-IV.

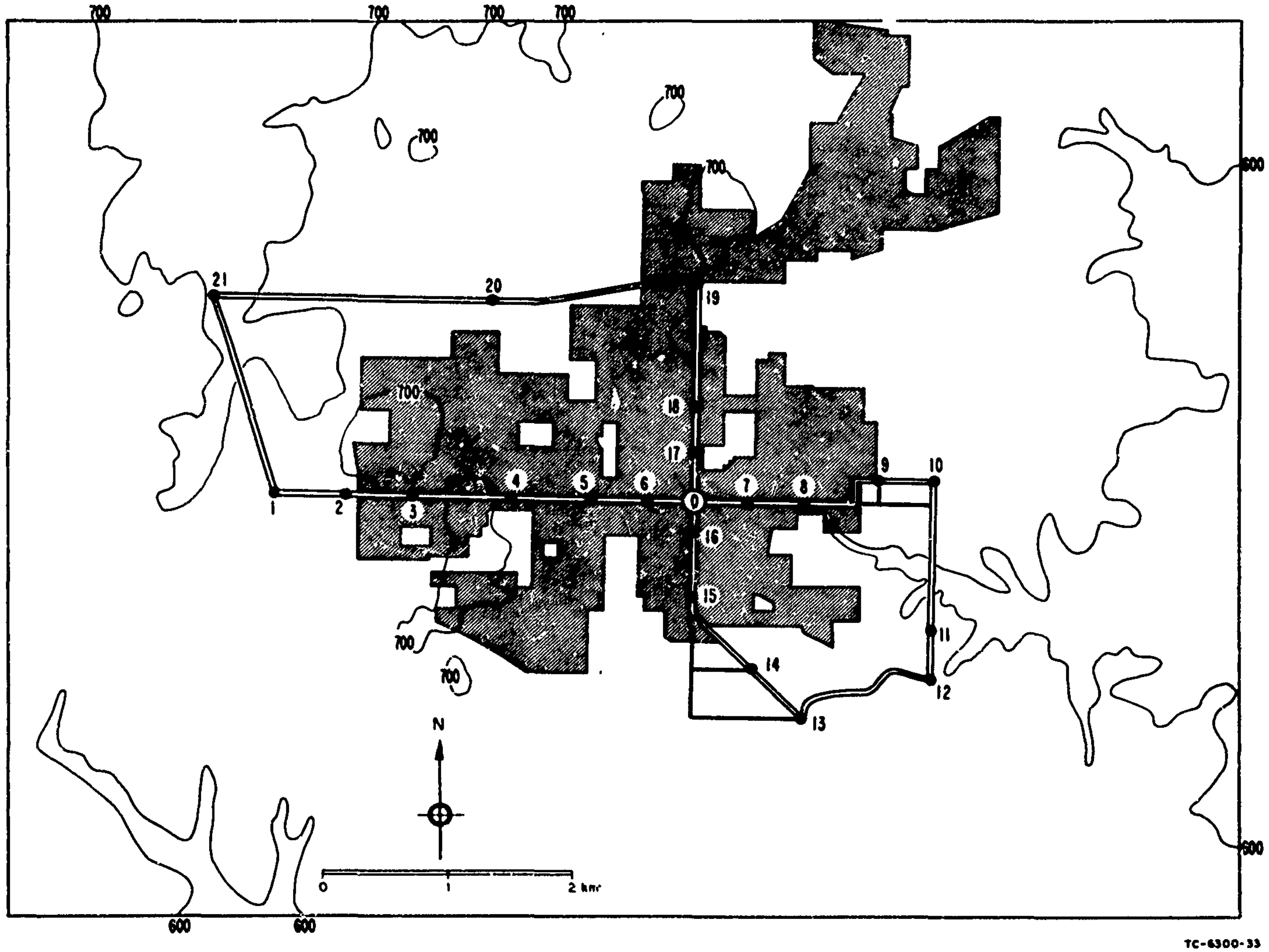

FIG. A-1 DENTON ROUTE

Table A-IV

DENTON, TEXAS, ROUTE DESCRIPTION

Point No.	Intersection	Approximate Elevation (ft)	Description
1	Oak-- Interstate 35E	680	W end of W-E cross-section line.
			Open area.
2	Oak--Hickory	690	
			Residential with large open areas.
3	Hickory--F	685	
			Residential with trees.
4	Hickory--C	690	
			Residential with trees, some commercial.
5	Hickory--Bernard	660	
			Residential with trees.
6	Hickory--Piner	645	
			Downtown area.
0	Hickory--Locust	650	
			Downtown area.
7	Hickory-- Exposition	620	
			Light industrial.
8	End of pavement on Hickory	615	
			Mixed residential and open areas.
9	Industrial--Wood	635	
10	Woodrow-- McKinney	615	
11	Woodrow--Morse	615	
12	Woodrow-- Shady Oak	615	Open area with few buildings.
13	Shady Oak-- Dallas	640	
14	Dallas--Smith	655	

Table A-IV (Concluded)

Point No.	Intersection	Approximate Elevation (ft)	Description
			Increasing commercial density.
15	Dallas becomes Locust	630	
			Commercial.
16	Locust--Sycamore	635	
0	Locust--Hickory	650	Downtown center.
17	Locust--Parkway	615	
18	Locust--Gary	640	Residential tree-lined street.
19	Locust--University	675	
			Commercial along street, residential off route.
20	University--Malone	650	
			Open area.
21	University--Interstate 35E	700	
			Open area along highway frontage road.
1	Interstate 35E--West Oak	680	

4. San Jose, California

A few measurements were made in San Jose in 1967. The route used for these measurements is somewhat different from that used for the 1966 program. The changes were made to conform better with the cross-sectional type of presentation used in the 1967 analysis. The points on the route have been renumbered and the new numbers are shown in Fig. A-2. This figure also shows topography, built-up areas, and the cross section lines. Figure A-3 pictures downtown San Jose. The route is described in Table A-V.

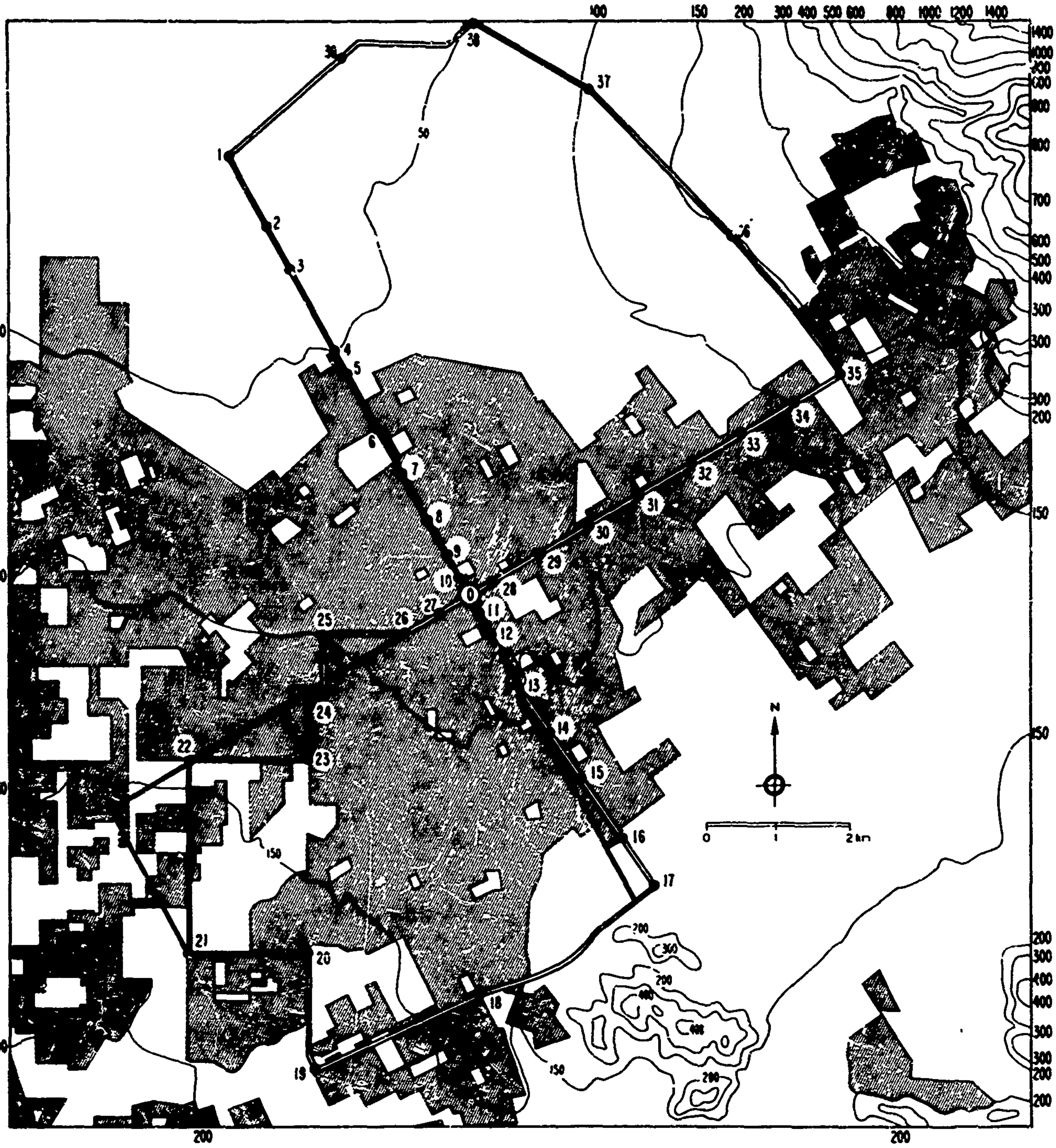

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FIG. A-2 SAN JOSE ROUTE

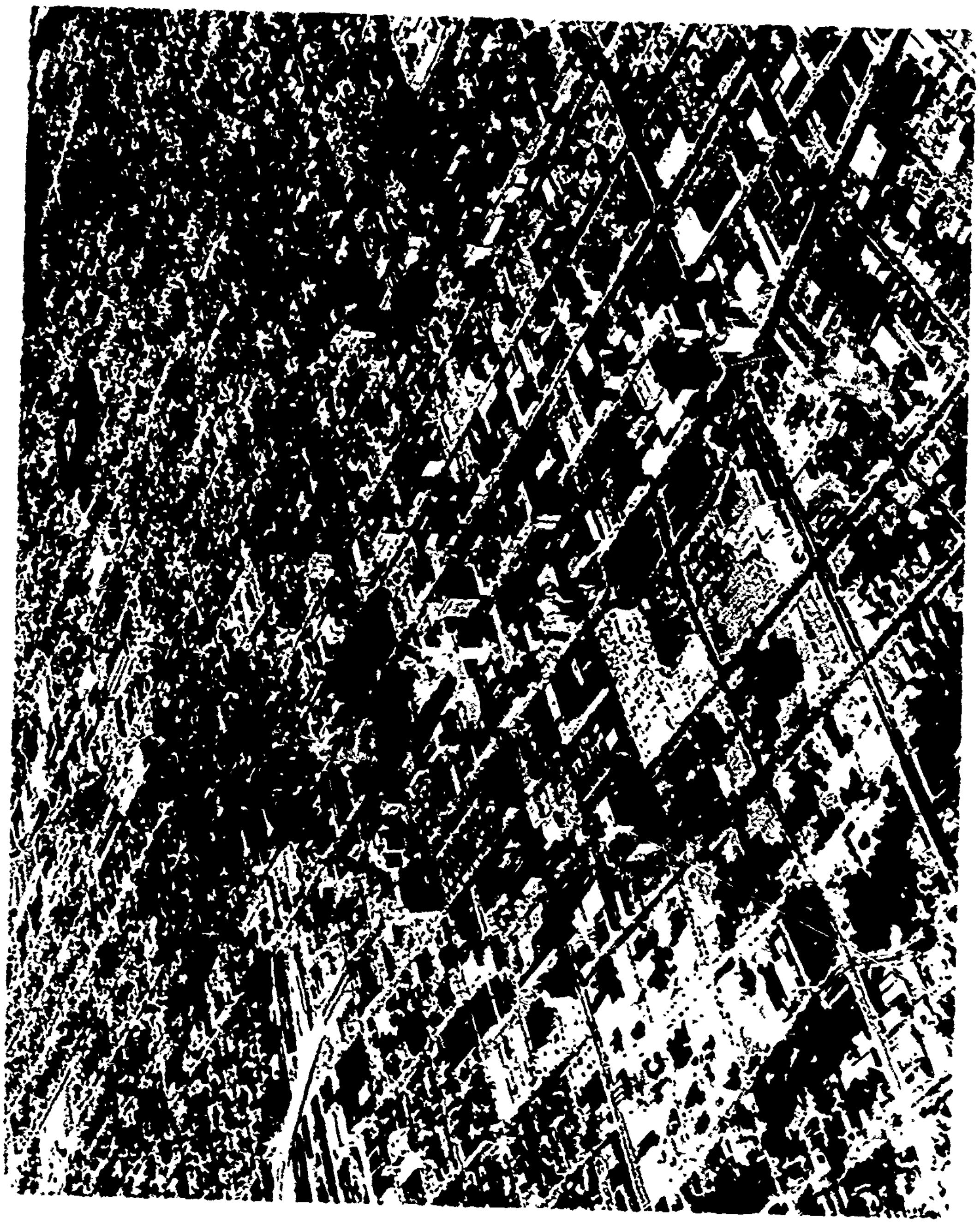

FIG. A-3 AERIAL VIEW OF SAN JOSE

Table A-V

SAN JOSE (1967) ROUTE DESCRIPTION

Point No.	Intersection	Approximate Elevation (ft)	Description
1	Trimble--1^{st} St.	30	NW end of NW-SE cross-section.
2	No cross street	35	Orchards and open fields.
3	1^{st}--Brokaw	40	
			Mixed commercial and open areas along route, open land off route to SW, mixed open and warehousing off route to NE.
4	1^{st}--Stern	50	
			Mostly apartments and motels along route with some commercial, residential off route to SW, mixed open and warehousing off route to NE.
5	1^{st}--Gish	55	
			Residential to last block, then large buildings, parking lots, and grassy spaces of county center to SW; commercial along NE side of route.
6	1^{st}--Younger	60	
			Large buildings, parking, and grassy areas of civic and county centers SW of route; residential to NE with some commercial.
7	1^{st}--Taylor	65	
			Mixed residential and commercial with many large trees.
8	1^{st}--Hensley	80	Commercial area at edge of downtown center, last block has park on NE side.
9	1^{st}--Julian	80	
10	1^{st}--St. John	85	
0	1^{st}--Santa Clara	90	Central downtown section with moderately large, 3- to 6-story, multistory buildings.
11	1^{st}--San Fernando	90	
12	1^{st}--San Carlos	95	

Table A-V (Continued)

Point No.	Intersection	Approximate Elevation (ft)	Description
			Commercial area at edge of downtown center.
13	1st--Margaret	100	
14	1st--Keyes	105	Commercial along route, older residential off route.
15	Monterey-- Cottage Grove	110	
			Mixed commercial, industrial, and warehousing.
16	Monterey-- Mitchell	110	Mixed commercial, industrial, warehousing, and open plots. SE end of NW-SE cross-section line. Industrial to NW, cemetery to SE for 2 blocks, then 3/4-mile open area, remainder residential.
17	Monterey-- Curtner	120	
18	Curtner--Lincoln	140	
19	Curtner-- Meridian	180	Residential with some interspersed orchard and park areas, some commercial around point 20.
20	Meridian-- Hamilton	165	First half has mixed apartments and single-family residential, with some commercial along route; second half has orchards to N and residential to S. SW end of SW-NE cross-section line. Large open and orchard areas intermixed with some commercial, last few blocks have county hospital grounds to W and City College campus to E.
21	Hamilton--Bascom	175	
22	Bascom--Moorpark	140	
			City college south of route for about 1/4-mile; remainder of area mostly mixed open and orchard with some residential in second half; last block commercial to N.
23	Moorpark-- Meridian	120	
			Commercial area.
24	Meridian-- San Carlos	115	

Table A-V (Continued)

Point No.	Intersection	Approximate Elevation (ft)	Description
			First block has parking lots, shopping center, and commercial; remainder is mixture of commercial and older residential.
25	Race--Alameda	100	
			Commercial along route, older residential off route; last two blocks is industrial and warehousing off route.
26	Alameda--Delmas	90	
			Edge of downtown area, commercial with some large, open, cleared areas.
27	Santa Clara--Almaden	85	Downtown center with moderately large, 3- to 6-story, multistory buildings.
0	Santa Clara--1st	90	
28	Santa Clara--4th	85	
29	Santa Clara--11th	85	Commercial along route, residential off route.
30	Santa Clara--19th	95	
31	Santa Clara--27th	90	
			Commercial along route, mostly residential off route, but industrial and warehousing off route to NE for first half of distance.
32	Santa Clara--34th	90	
			Commercial along route, residential off route.
33	Santa Clara--Sunset	95	Commercial along route with many large open areas off route, also some warehousing and some residential.
34	Santa Clara--Foss	100	
35	Santa Clara--Capitol	130	NE end of SW-NE cross-section line.
36	Capitol--Maybury	155	About 1/2-mile of mixed residential and large open areas, remainder mixed orchards and large open plots.
37	Capitol--Hostetter	110	

Table A-V (Concluded)

Point No.	Intersection	Approximate Elevation (ft)	Description
			Orchards and open areas, some commercial and residential near Pt. 38.
38	Capitol--Trimble	50	Orchards and open areas with a few small commercial areas and a few residential tracts along route.
39	Trimble--Nimitz Freeway	35	
1	Trimble--1^{st}	30	

C. Instrumentation

The mobile temperature measuring equipment used for the 1967 studies is the same as that described in the 1966 studies (Ludwig, 1967). Briefly, wet- and dry-bulb temperatures were measured at 0.3 and 2 meters above the surface using composite thermistor elements with linear response characteristics between -5 and +45°C. The values were recorded on strip charts. The accuracy of the system was about ±0.25°C for the dry bulb and ±0.5°C for the wet bulb. The estimated response times are about 10 and 30 seconds, respectively. The sensors were shielded and ventilated (with a minimum lineal air speed of about 3.5 m/sec) to minimize the effects of radiative heating.

One hygrothermograph was placed in a standard U.S. Weather Bureau Shelter on the roof of the airport at Love Field in Dallas. Hourly values of all the meteorological variables were obtained from official Weather Bureau records for Love Field in Dallas and for Greater Southwest International Airport, Meacham Airport, and Carswell Air Force Base in Ft. Worth.

A pyrheliograph was placed on the roof of the terminal building at Love Field, Dallas. This instrument consists of two bimetallic strips, one blackened to absorb solar and sky radiation, the other protected from absorption of incoming radiation by a highly polished shield. The linkage between the two elements is such that the pen reacts only to temperature differences between the dark element which responds to both solar radiation and ambient temperature and the reflecting element which responds to ambient temperature alone. The manufacturer* claims an accuracy of ±5% for this pyrheliograph. The instrument responds principally to radiation with wavelengths between about 0.36 and 2 μ.

* Belfort Instrument Co., Baltimore, Md.

D. Field Operations

The routes used in the cities studied have already been described. The routes for the 1967 studies were specifically selected to provide information for the time cross sections presented in Section II and Appendix B. Identifiable points were selected where temperature readings were to be recorded; these points were usually marked by an intersection. For the 1967 program an attempt was made to locate the points at about 1/2-mile intervals along the cross-section lines. In some cases, these points were located at 1/4-mile intervals through the center of town. A much greater spacing was used along the peripheral parts of the routes. Identifying marks were made on the continuous temperature records as the numbered points were passed.

In 1966, field operations were generally confined to daylight hours. Measurements were made on a nearly round-the-clock basis on several days of 1967. On these occasions, one of the two meteorologists worked from about 0300 to 1230 LST (local standard time) with some time taken off for meals and to change the charts on the instruments at the airport. The other meteorologist generally worked from about 1430 to 0030 LST with time taken for dinner. On three occasions measurements were made from before sunrise to after sunset with one meteorologist surveying Dallas and the other Ft. Worth. Occasionally concurrent measurements were made in Dallas and Denton. Table A-VI gives the approximate periods of operation for the cities surveyed during 1967.

Of course, this year's extension of the coverage to night hours or simultaneous measurement in two cities meant a corresponding reduction of effort somewhere else, since the same number of field personnel were available both years. The reduction came in the frequency with which the routes could be traversed. Generally, the interval between measurements at any given location was about one hour last year and about two hours this year.

TABLE A-VI

PERIODS OF FIELD OPERATION DURING 1967

Date (1967)	Dallas (time, LST)	Ft. Worth (time, LST)	Denton (time, LST)	San Jose (time, LST)
June 16				0800-1155
July 12	1100-2140			
13	0355-0910			
14	1000-1750			
17	0855-2355			
18	0350-1240, 1510-2350			
19	0355-0505, 1300-2330			
20	0655-1140, 1440-2340			
21	0525-1140, 1535-2400			
22	0000-0020			
23	1940-2400			
24	0000-0010, 0300-1205, 1400-2400			
25	0000-0010, 0300-1230, 1410-2400			
26	0000-0030, 0240-1250, 1425-2400			
27	0300-1225, 1430-2400			
28	0000-0040, 0300-1255, 1435-2400			
29	0300-1210, 1340-2400			
30	0000-0035, 0300-0905, 1335-2400			
July 31	0000-0035			
Aug. 2	0740-2400			
3	0000-0105, 0515-1010	1310-1605	1655-1735	
4	0305-2225	0400-2125		
5	1330-2400		1300-2035	
6	0000-0050, 0300-1300, 1420-2400			
7	0000-1220, 1420-2400			
8	0000-0020			
9	0320-2225	0355-2200		
11	0325-2135	0355-2205		
13	0320-0940		0405-0905	
Sept. 8				0300-1210, 1410-2400
9				0000-0035, 0305-1220

E. Sources of Geographical Information

Rand McNally Commercial Atlas and Marketing Guide, 97th ed., Rand McNally and Co., Chicago, 1966

U.S. Geological Survey maps, Washington, D.C.

Columbus and vicinity, Ohio, 1955
Ft. Worth and vicinity, Texas, 1955
Indianapolis and vicinity, Indiana, 1959
Springfield, Ohio (1:24000 map), 1955
White Rock Lake, Texas (1:24000 map), 1957
Dallas, Hutchins, Oak Cliff, Texas (1:24000 map) 1958
Duncanville, Hurst, Irving, Kennedale, Texas (1:24000 map) 1959
Denton East, Denton West, Texas (1:24000 map) 1960
New Moorefield, Ohio (1:24000 map) 1961

Sunshine and Cloudiness at Selected Stations in the United States, Alaska, Hawaii, and Puerto Rico, Technical Paper No. 12, U.S. Weather Bureau, Washington, D.C., 1951

Climatography of the United States No. 86-10, Decennial Census of U.S. Climate--Climatic Summary of the U.S., supplement for 1951 through 1960, Indiana, U.S. Government Printing Office, Washington, D.C., 1964

Climatography of the United States No. 86-29, Decennial Census of U.S. Climate--Climatic Summary of the U.S., supplement for 1951 through 1960, Ohio, U.S. Government Printing Office, Washington D.C., 1964.

Climatography of the United States No. 86-36, Decennial Census of U.S. Climate--Climatic Summary of the U.S., supplement for 1951 through 1960, Texas, U.S. Government Printing Office, Washington, D.C., 1965

Appendix B

TEMPERATURE AND HUMIDITY ANALYSES

Appendix B

TEMPERATURE AND HUMIDITY ANALYSES

This Appendix gives detailed analyses of the 1967 data. The solid lines in these figures are isotherms, labeled in degrees centigrade. The dashed lines are isohumes, labeled in millibars of partial pressure of water vapor. The topography and general nature of the areas on the cross-section lines are shown along the right sides of the cross sections. The numbers refer to the points on the routes described in Appendix A.

On the Dallas figures insolation is shown as measured at Love Field. U.S. Weather Bureau or Air Force observations are plotted on some of the cross sections. The wind directions have been plotted relative to the direction of the cross-section line. A wind plotted as blowing along the line was parallel to it; a wind plotted at right angles to the line was blowing across it. Wind speeds are shown by flags on the direction shafts, one full barb for each ten knots and a half barb for five knots. Sky cover is shown in the station circle, ranging from an open circle for clear skies to an "⊕" for overcast. Temperatures are plotted near the station circle in degrees Centigrade; however, they were originally reported only to the nearest degree Farenheit and are therefore only accurate to about 0.5°C.

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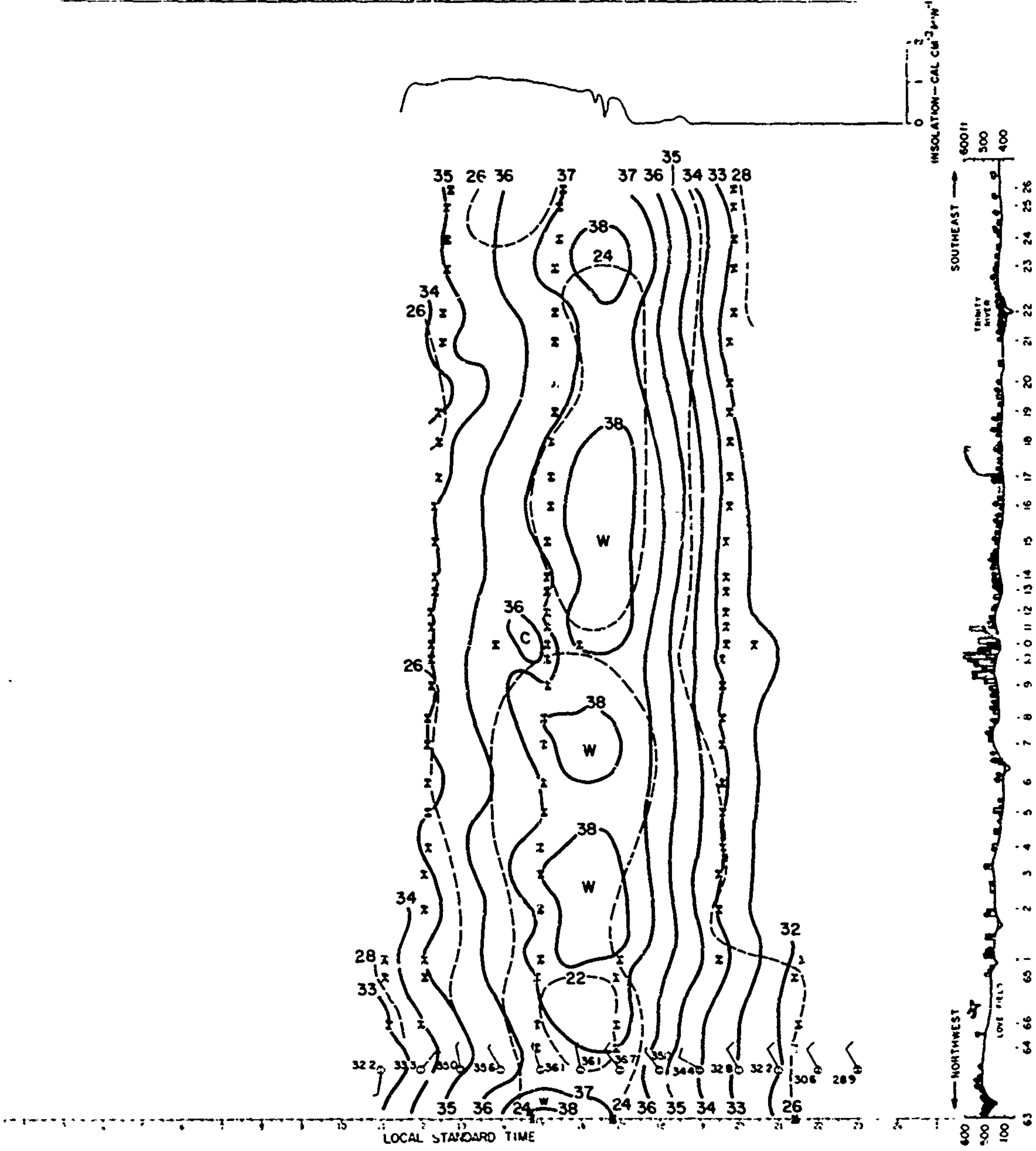

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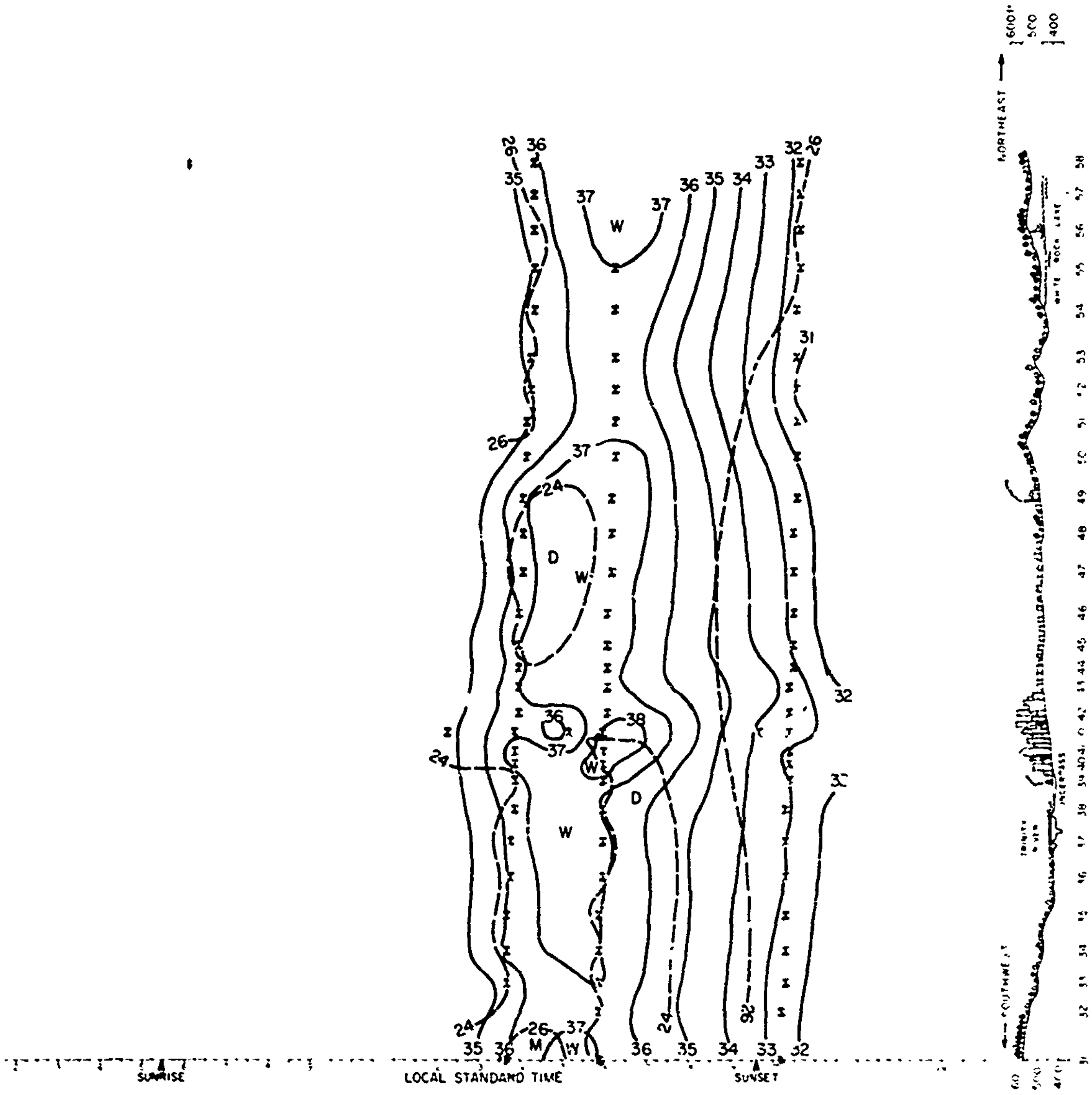

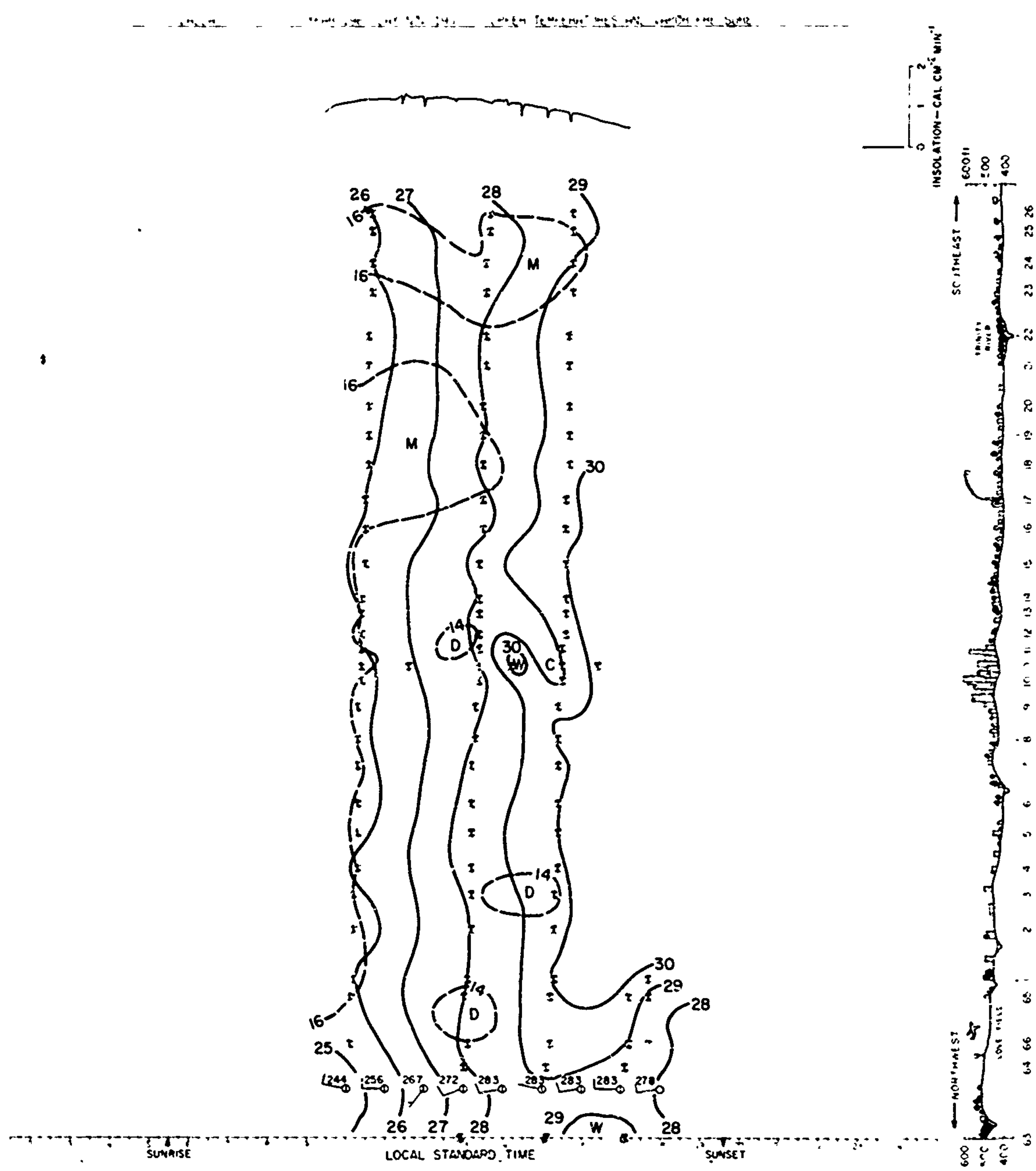
SUNRISE
LOCAL STANDARD TIME
SUNSET
INSOLATION—CAL CM^{-2} MIN^{-1}
SOUTHEAST
NORTHWEST

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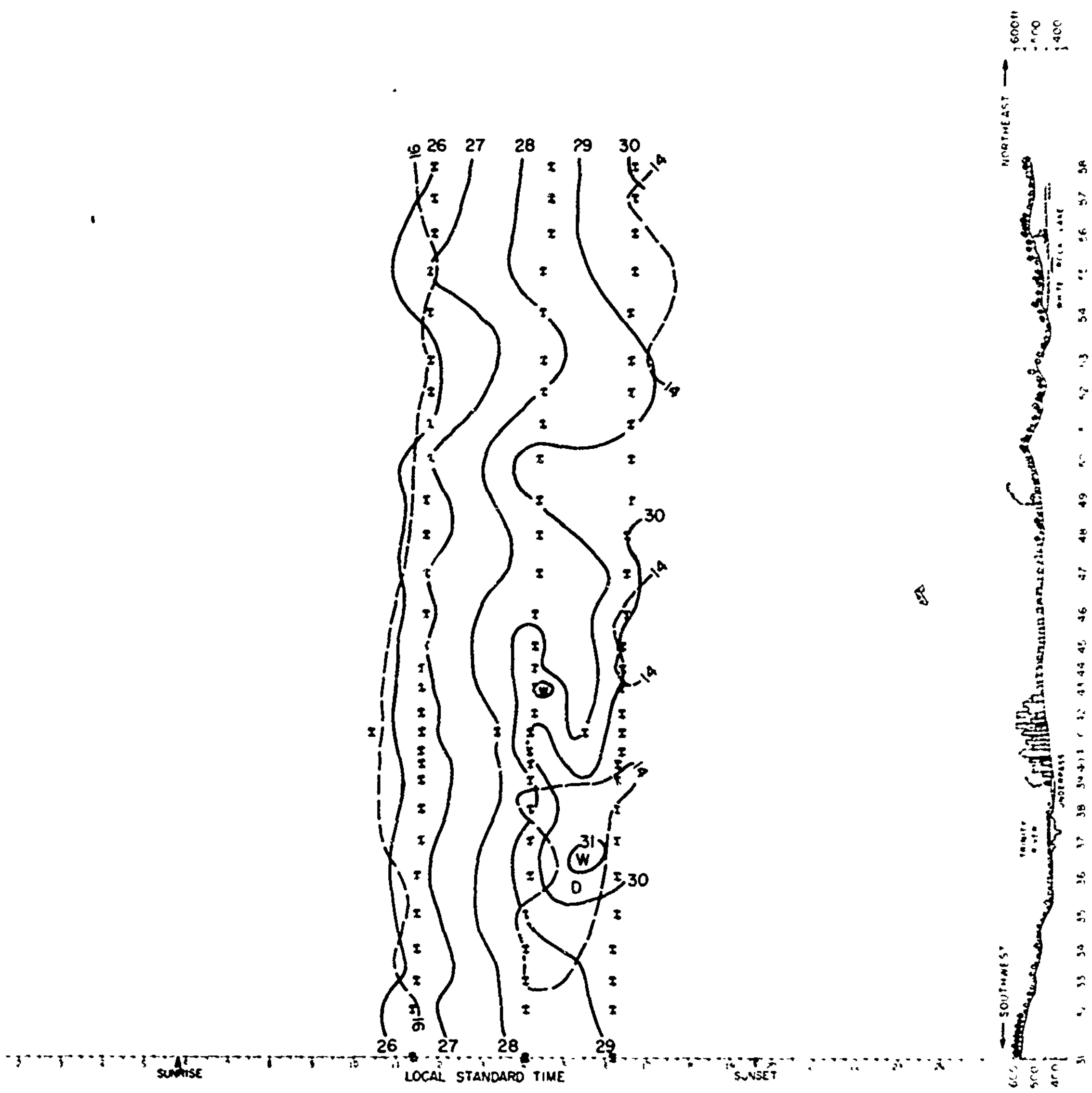

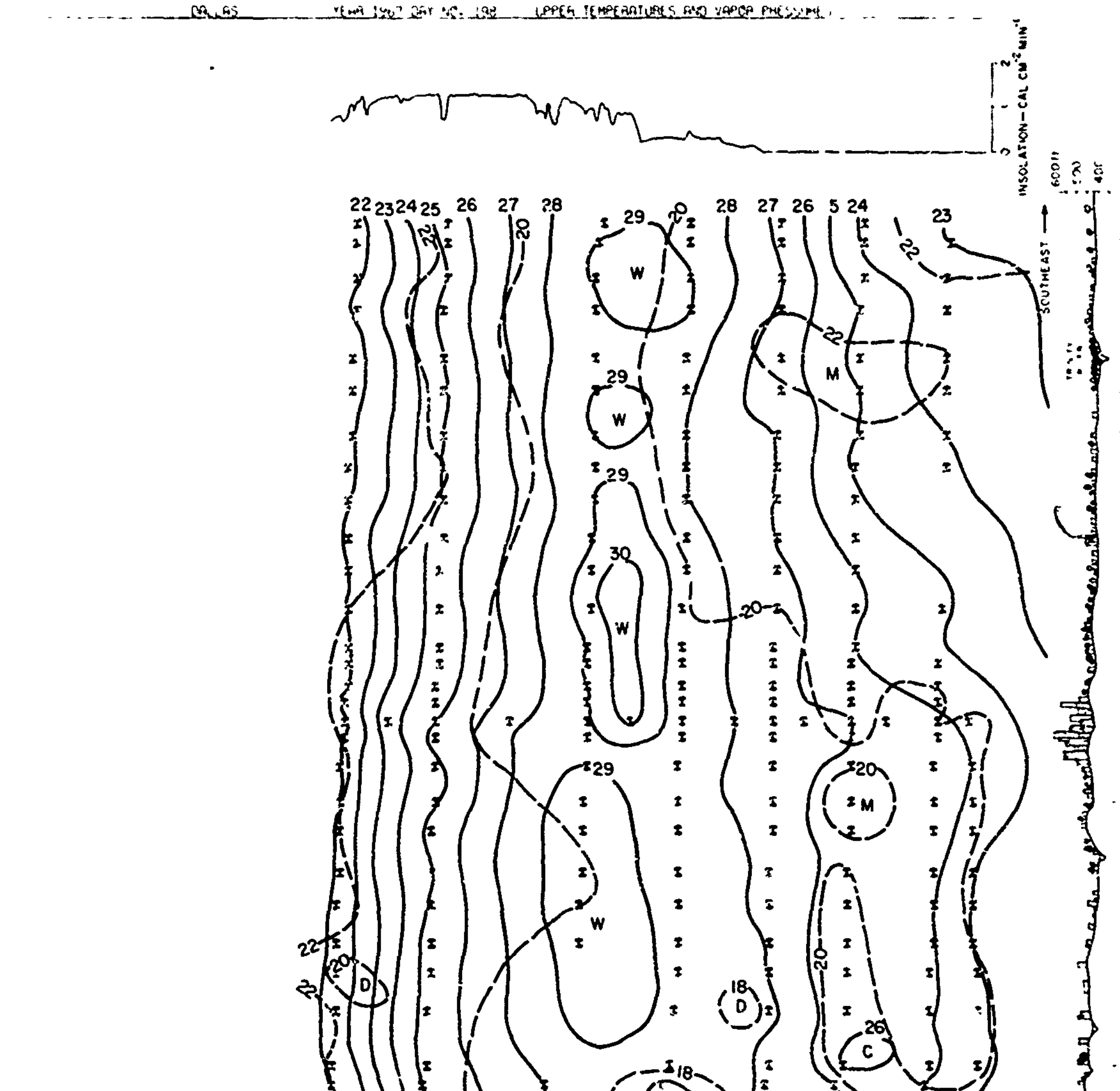
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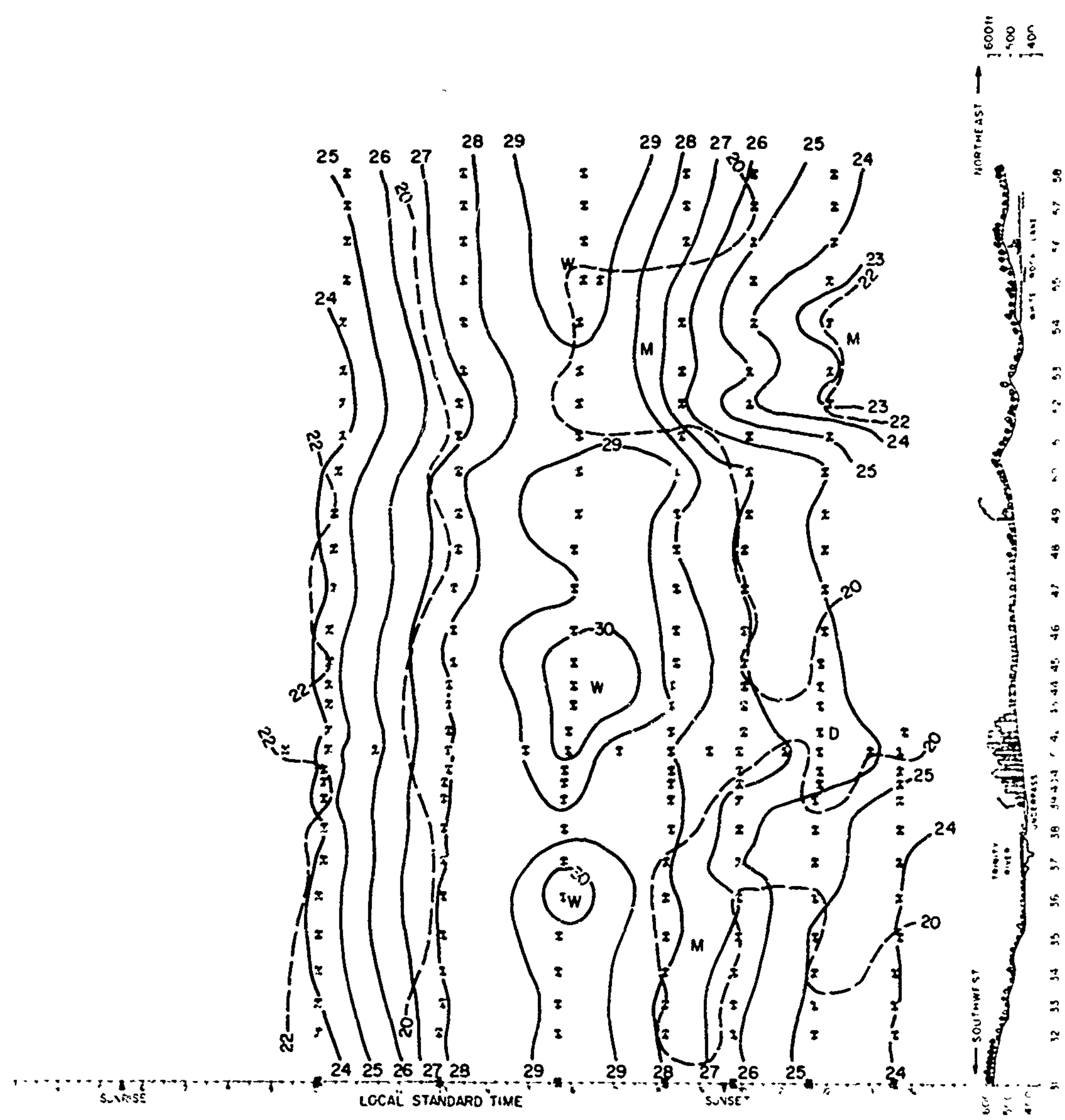
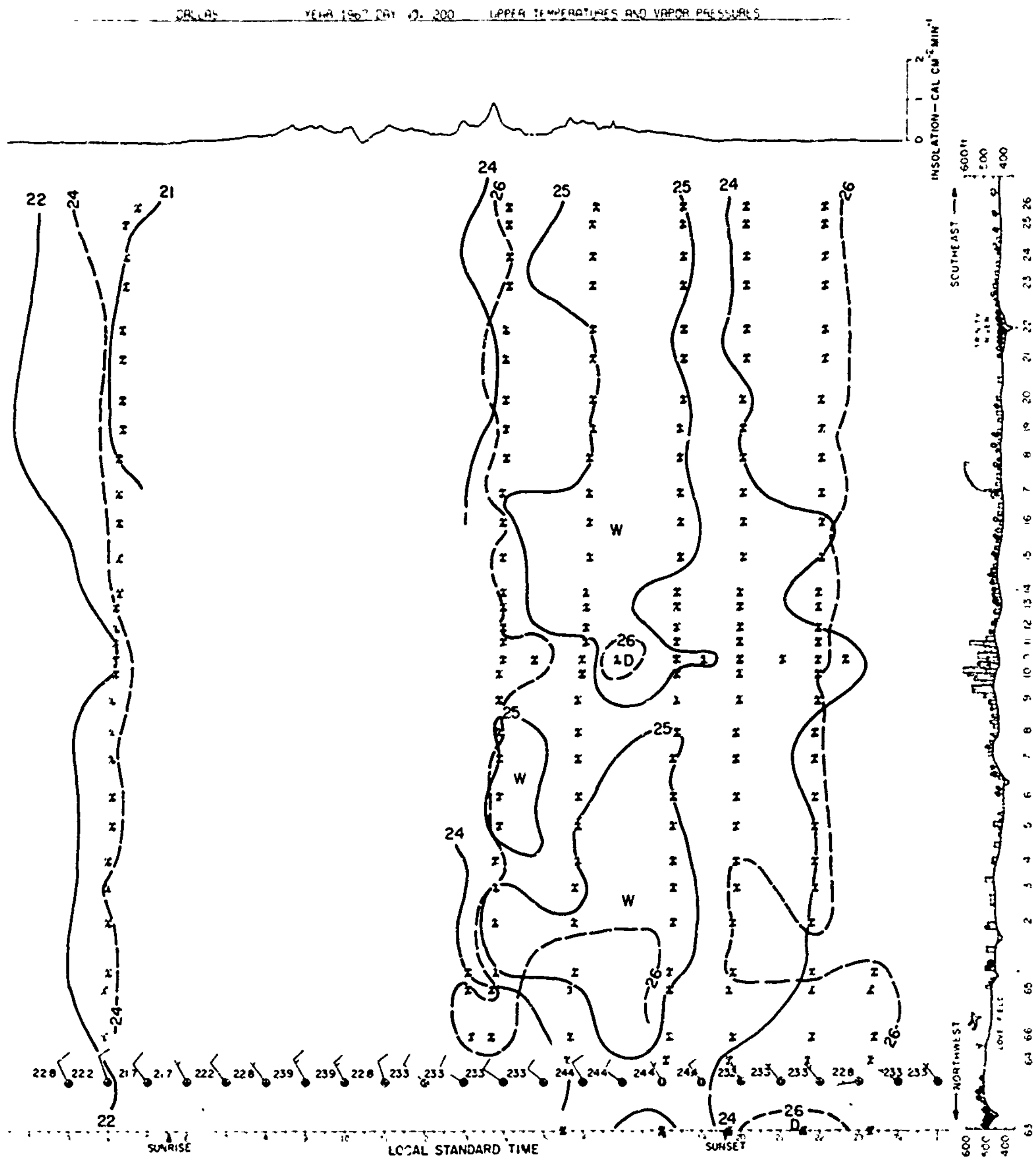
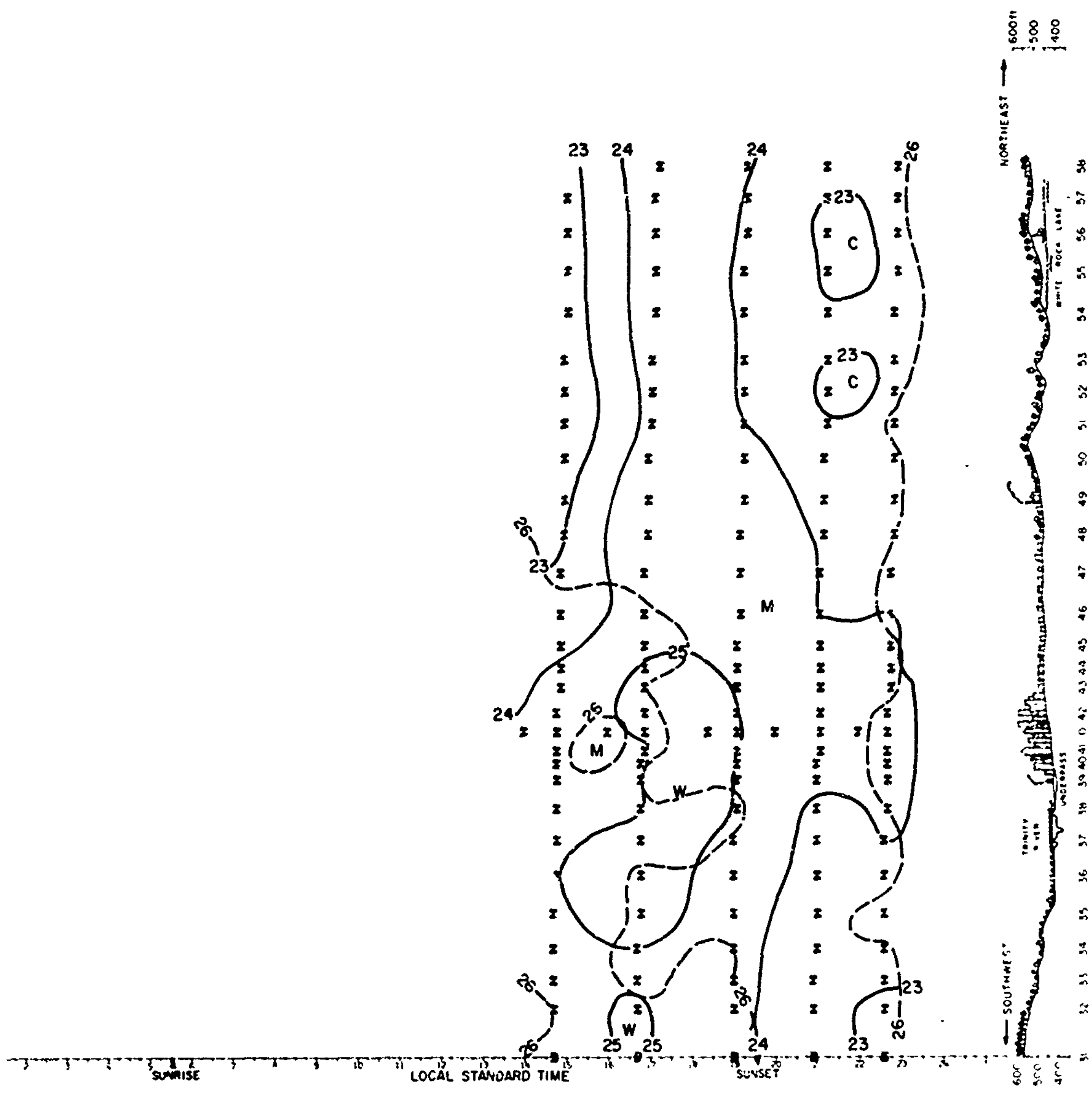
INSOLATION—CAL CM⁻² MIN⁻¹
SOUTHEAST
NORTHWEST
SUNRISE
LOCAL STANDARD TIME
SUNSET
W
M
D
C

DALLAS YEAR 1967 DAY NO 198 UPPER TEMPERATURES AND VAPOR PRESSURE




DALLAS
UPPER TEMPERATURES AND VAPOR PRESSURES
INSOLATION—CAL CM⁻² MIN⁻¹
SUNRISE
LOCAL STANDARD TIME
SUNSET
SOUTHEAST
NORTHWEST

DALLAS YEAR 1967 DAY NO. 200 UPPER TEMPERATURES AND VAPOR PRESSURES



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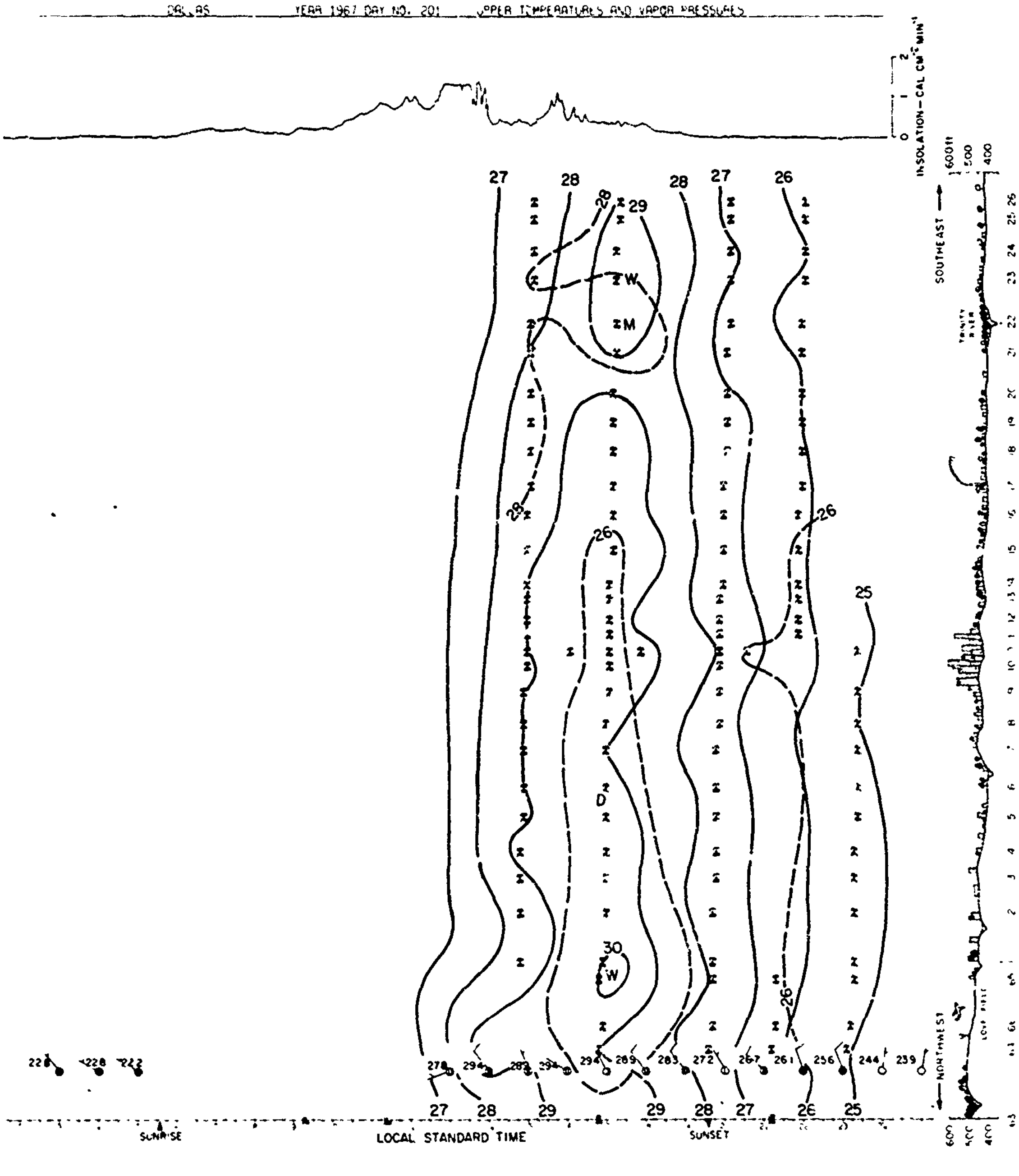

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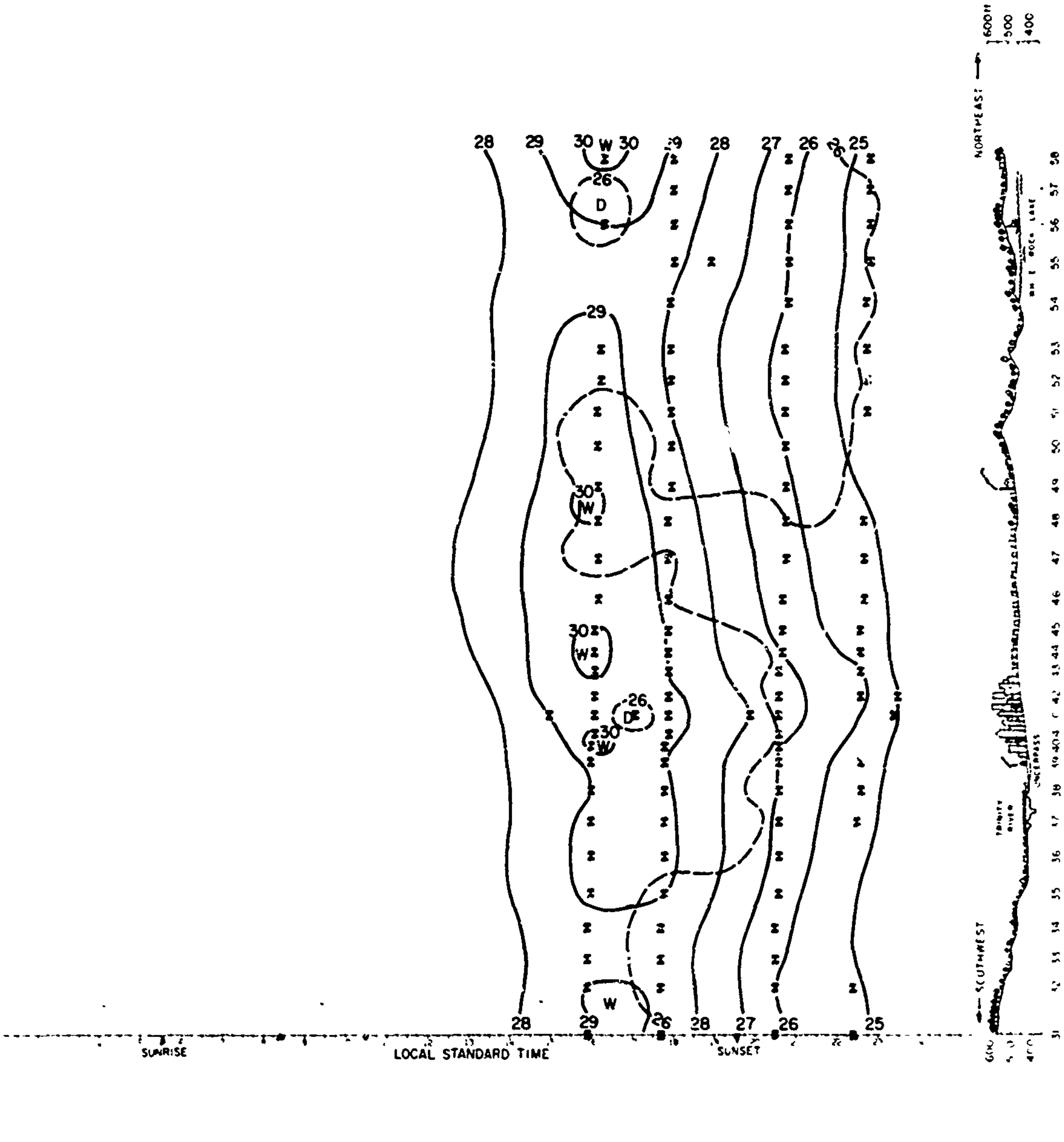
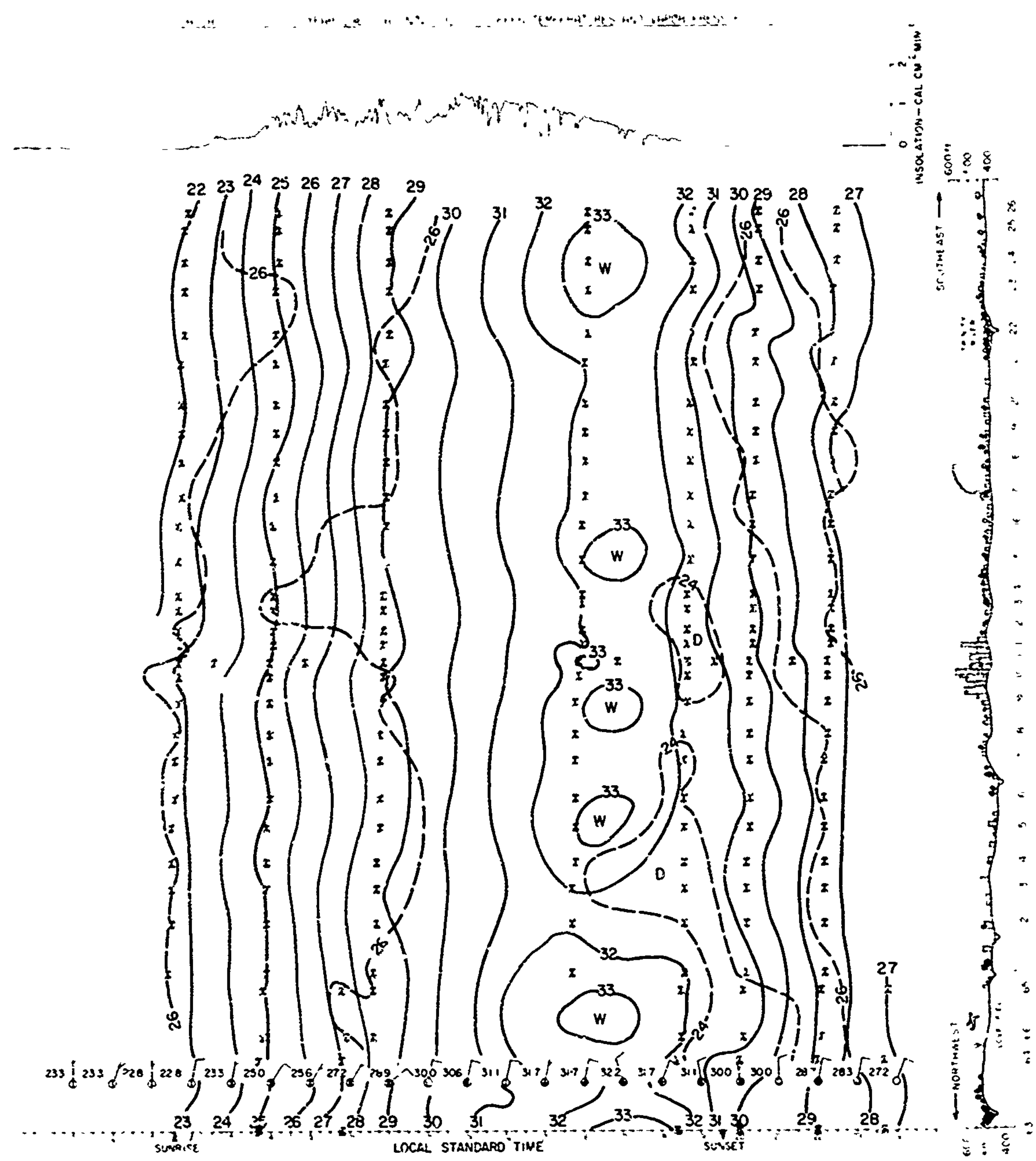
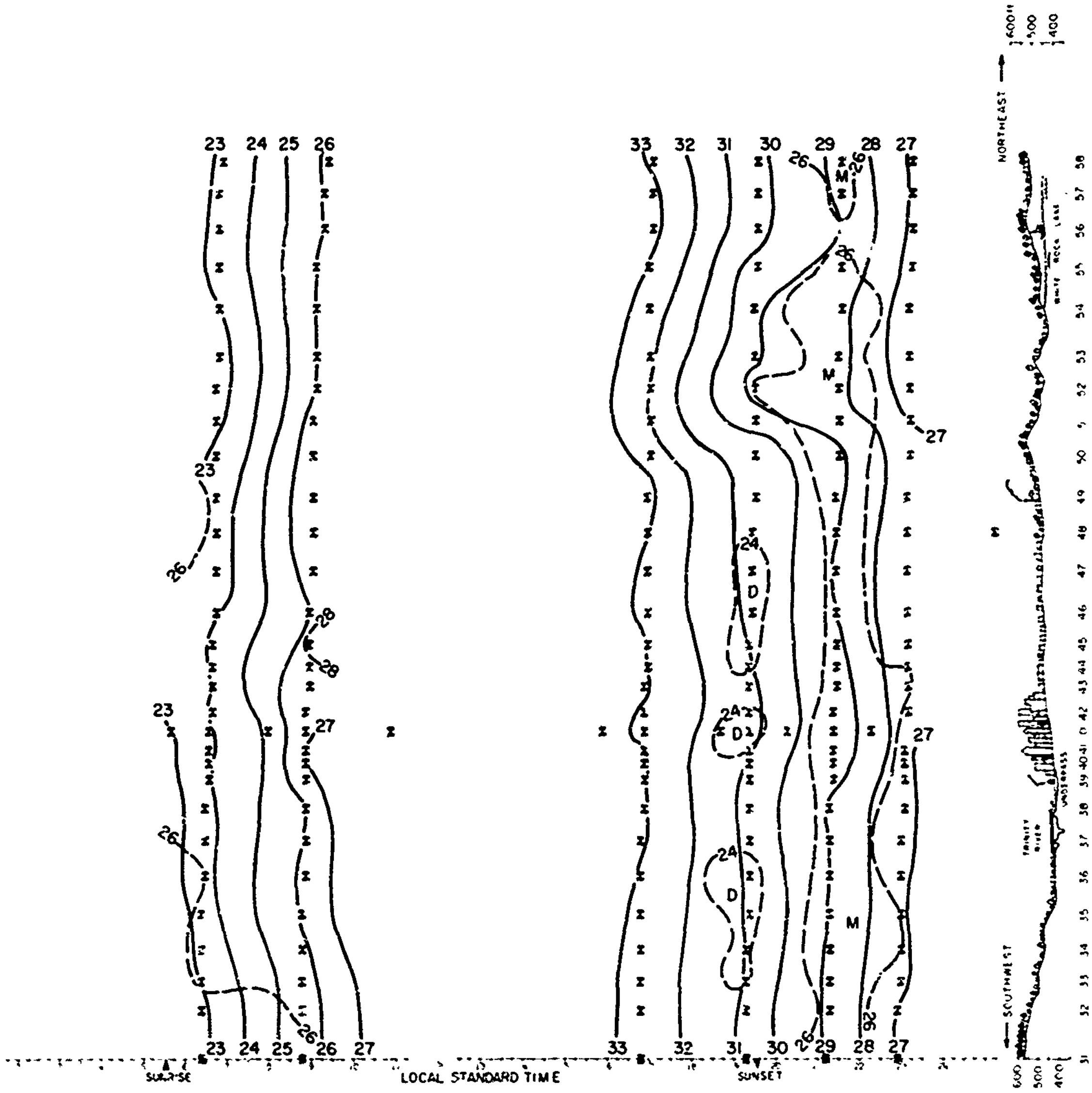
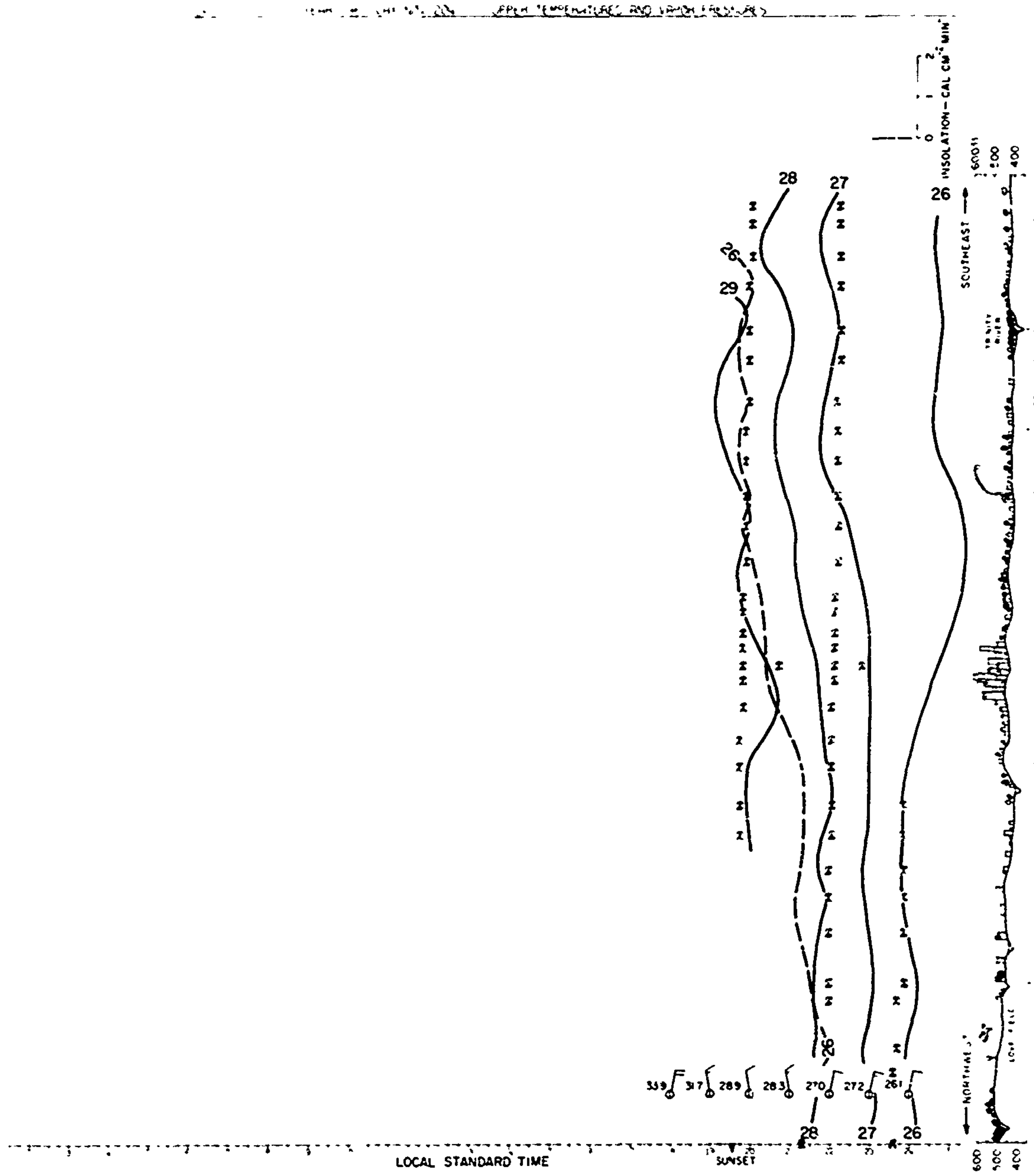


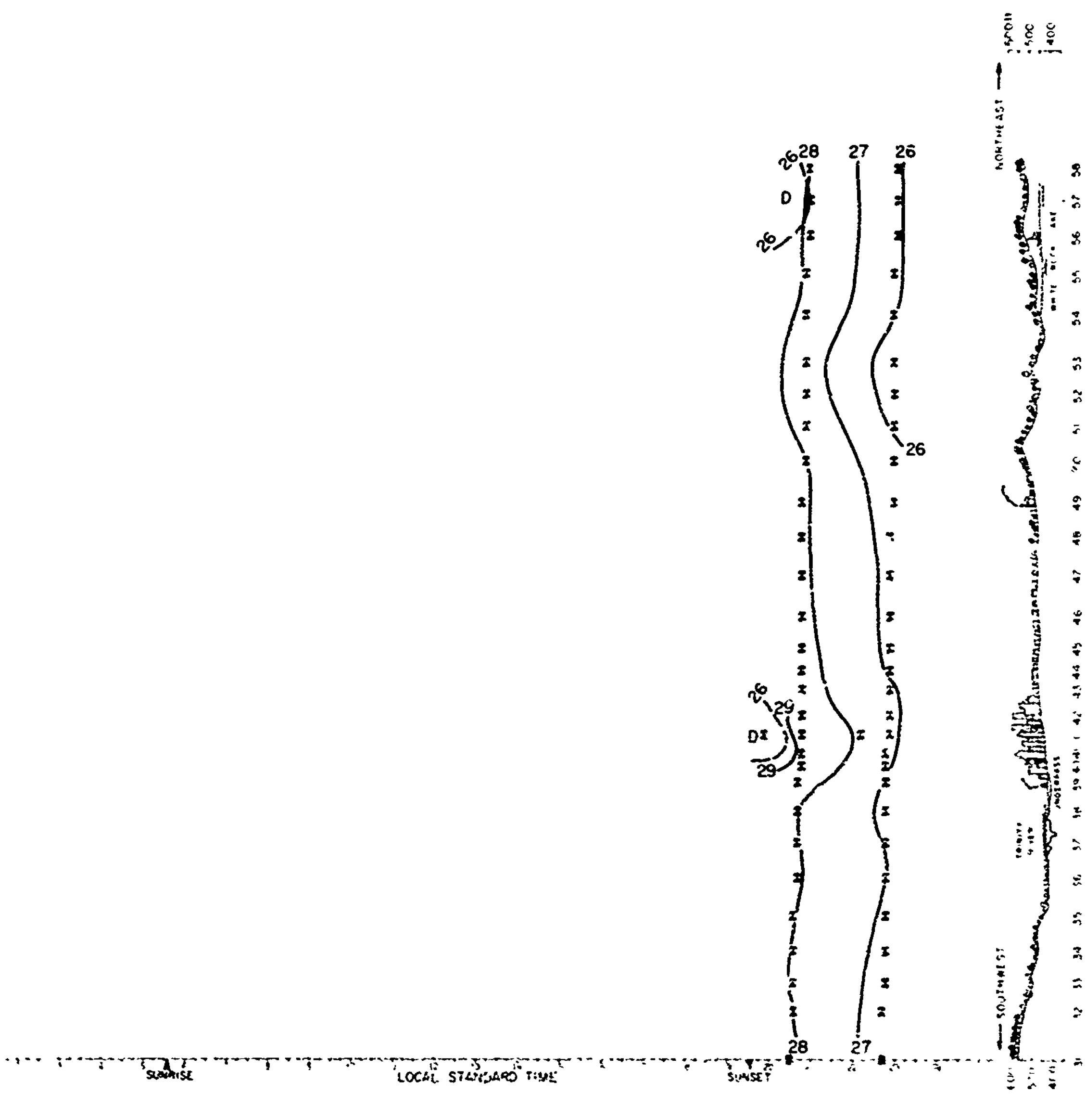

LOCAL STANDARD TIME
SUNRISE
SUNSET
W
D
NORTHWEST
SOUTHEAST

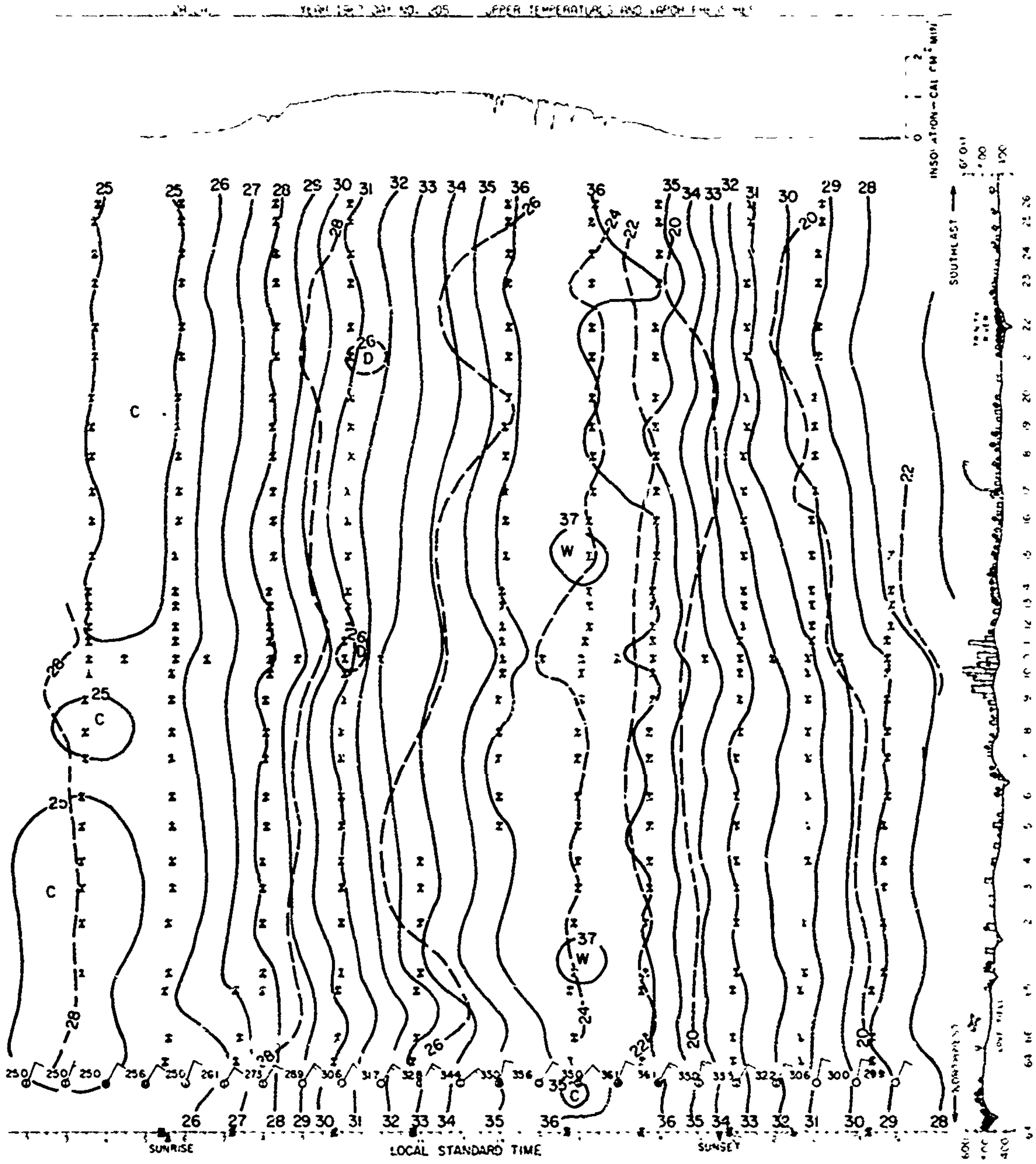
YEAR 1967 DAY NO. 202 UPPER TEMPERATURES AND VAPOR PRESSURES




LOCAL STANDARD TIME
SUNSET
SOUTHEAST
NORTHEAST
INSOLATION-CAL CM^{-2} MIN^{-1}

DALLAS YEAR 1967 DAY NO. 204 UPPER TEMPERATURES AND VAPOR PRESSURES




SUNRISE
LOCAL STANDARD TIME
SUNSET
SOUTHEAST

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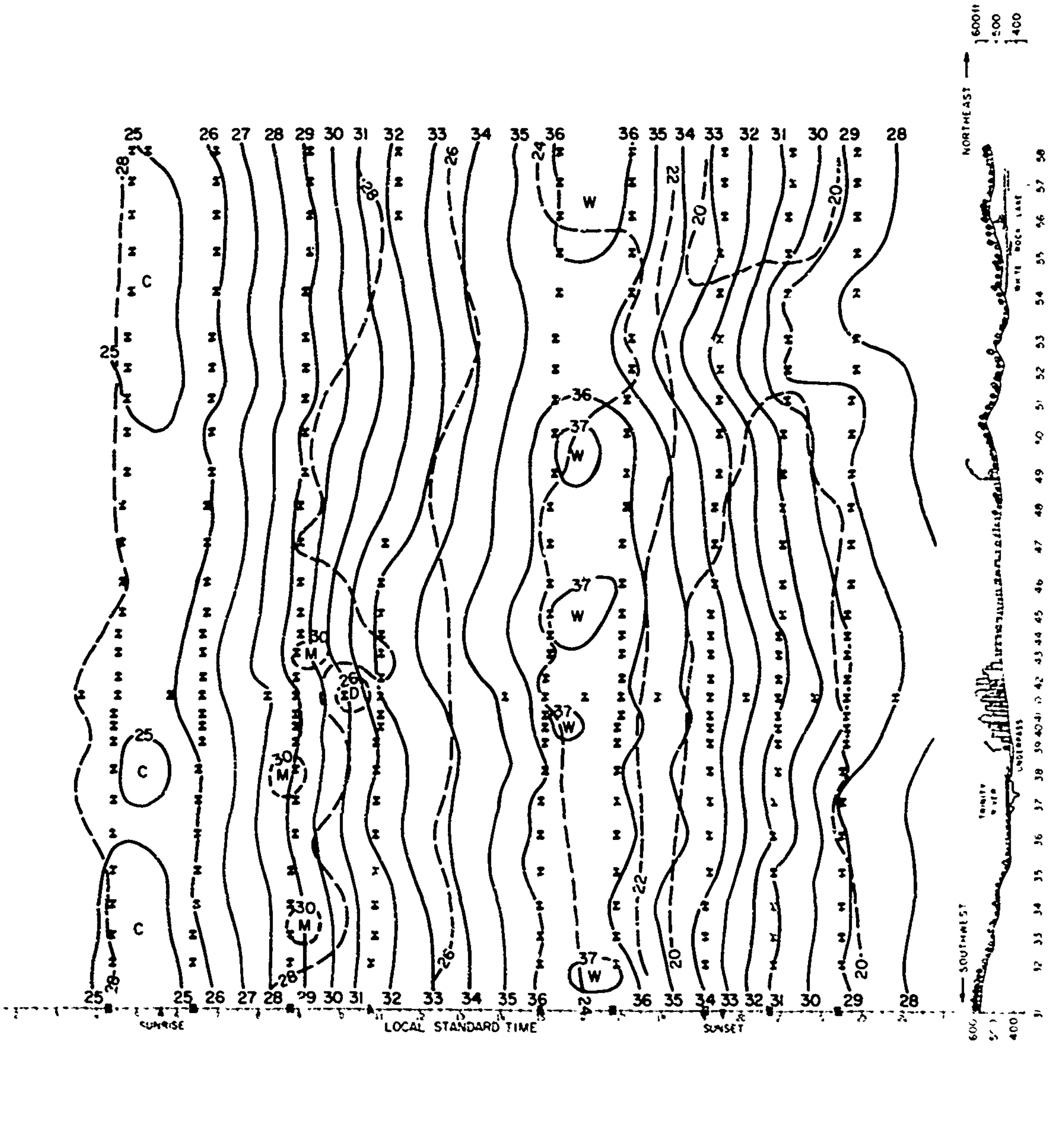
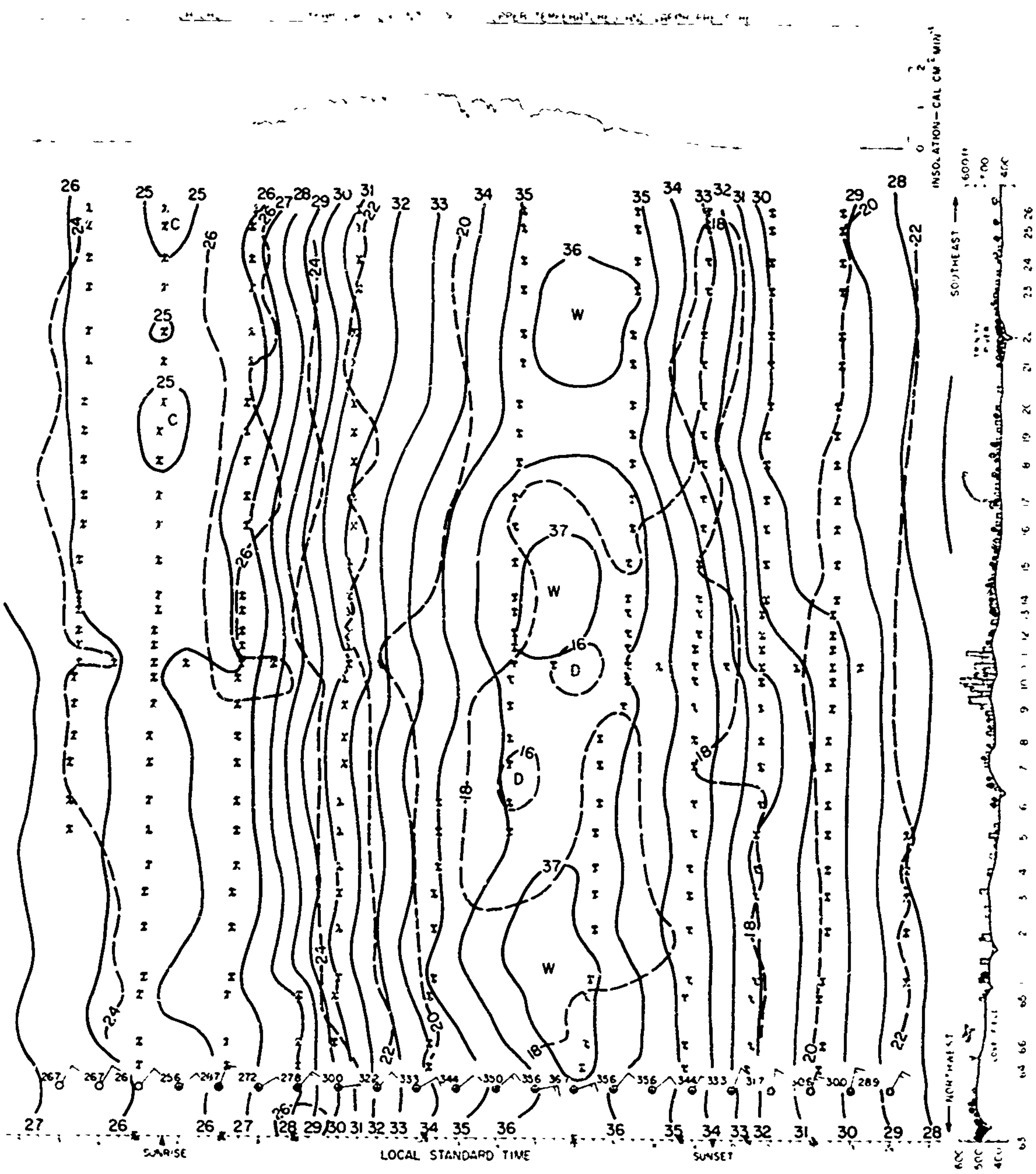
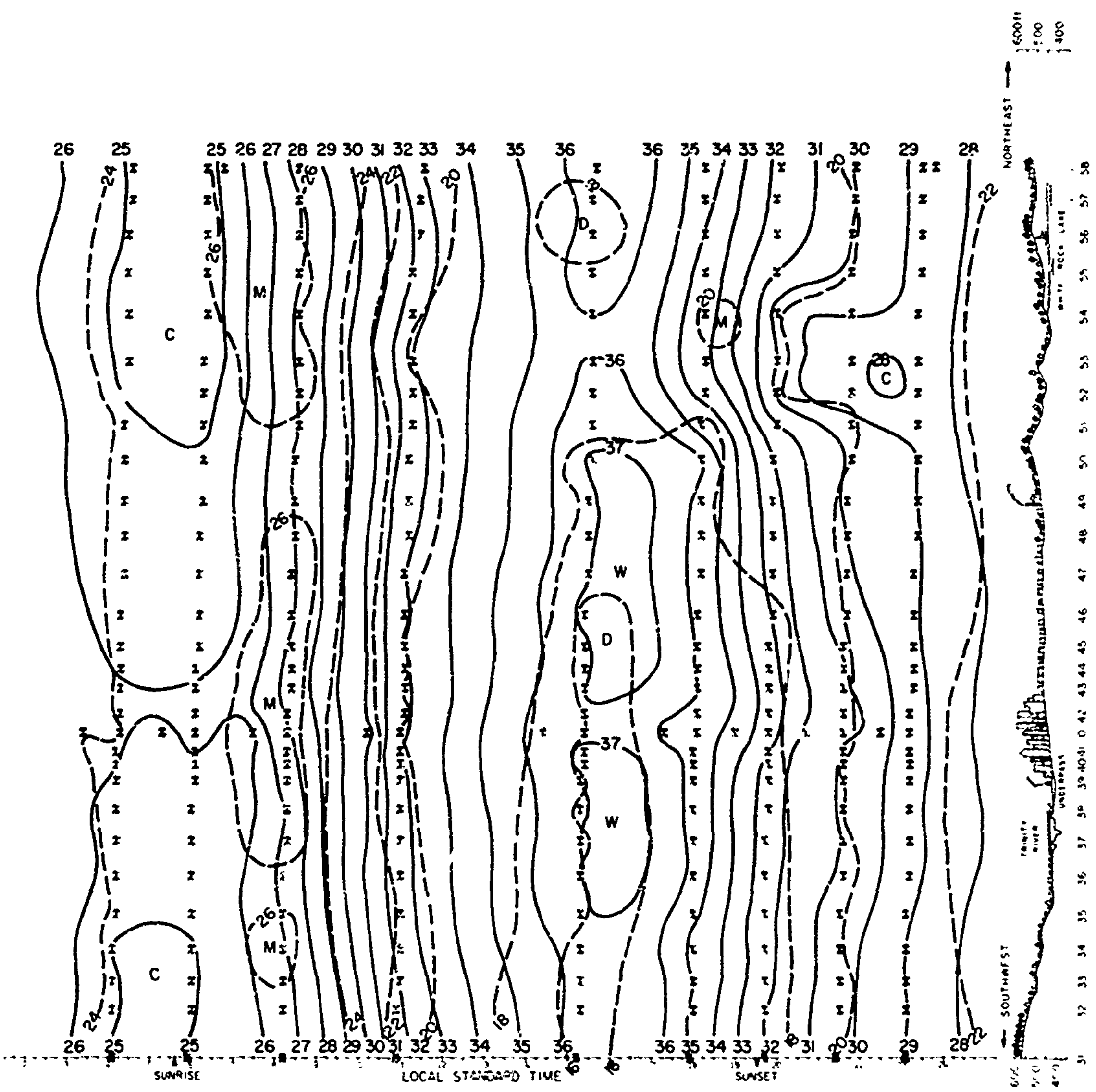
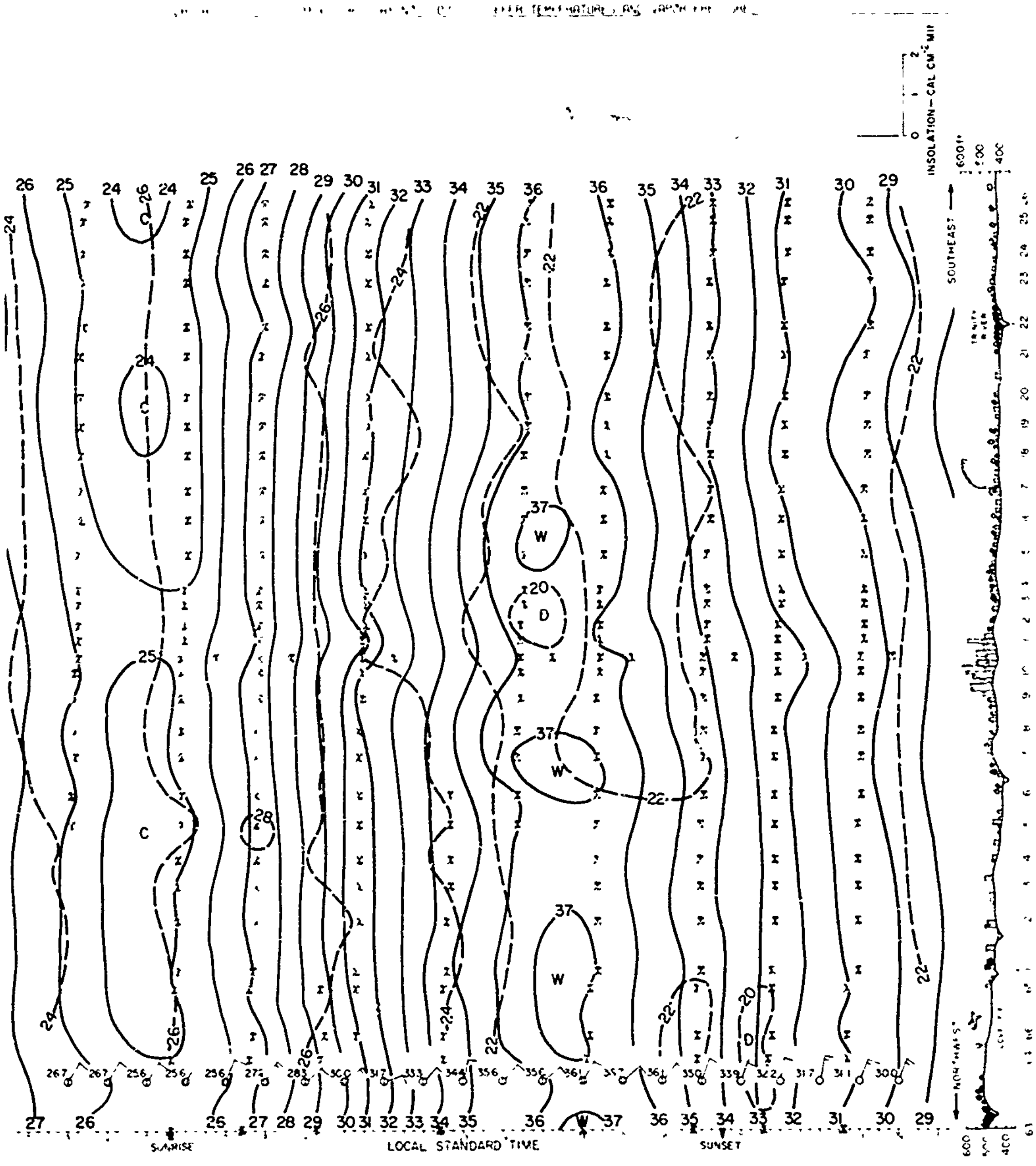



LOCAL STANDARD TIME
SUNRISE
SUNSET
SOUTHEAST
NORTHEAST
INSOLATION—CAL CM⁻² MIN⁻¹

DALLAS YEAR 1967 DAY NO. 206 UPPER TEMPERATURES AND VAPOR PRESSURES




LOCAL STANDARD TIME
SUNRISE
SUNSET
SOUTHEAST
NORTHWEST
INSOLATION—CAL CM⁻² MIN⁻¹

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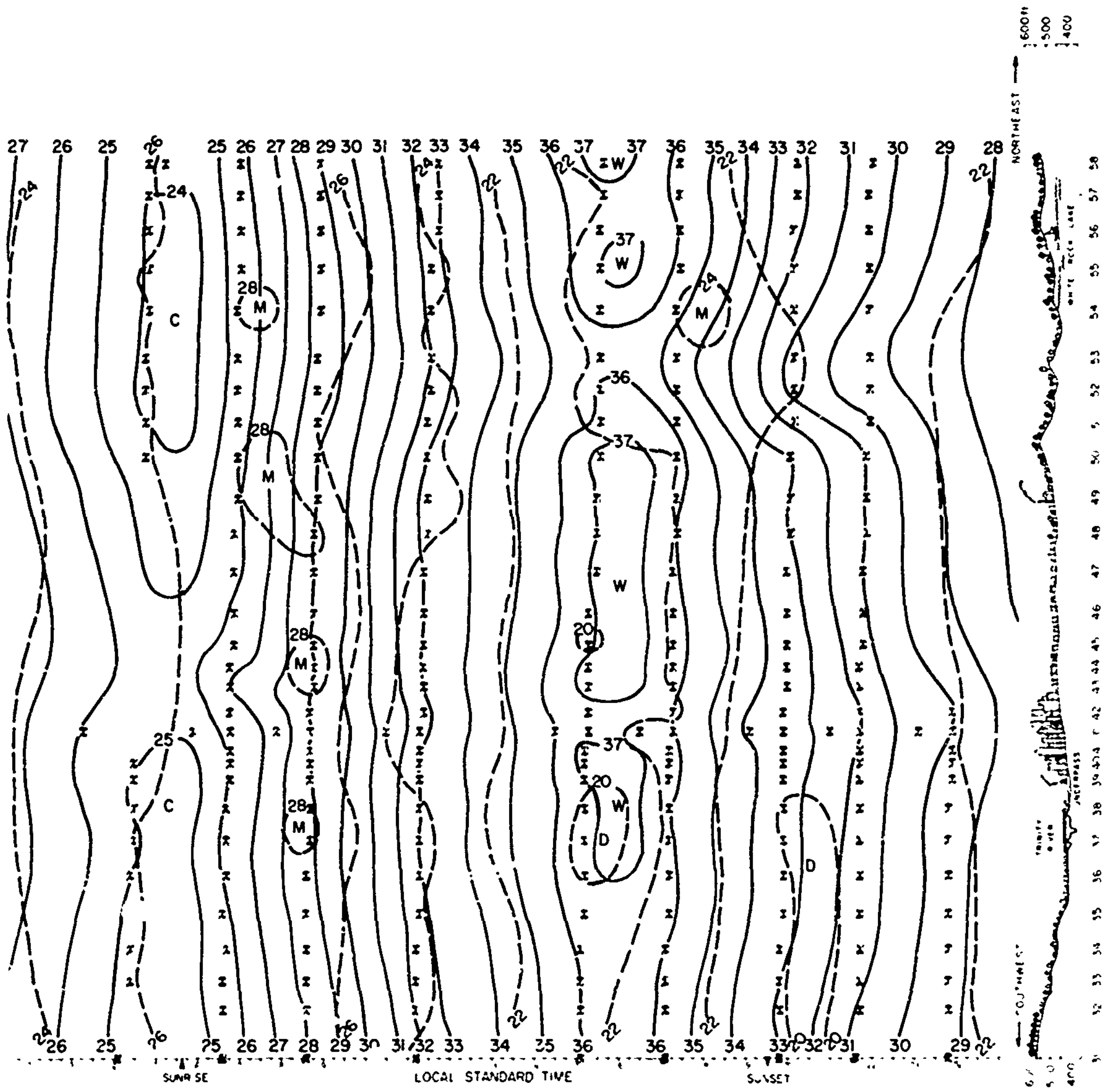

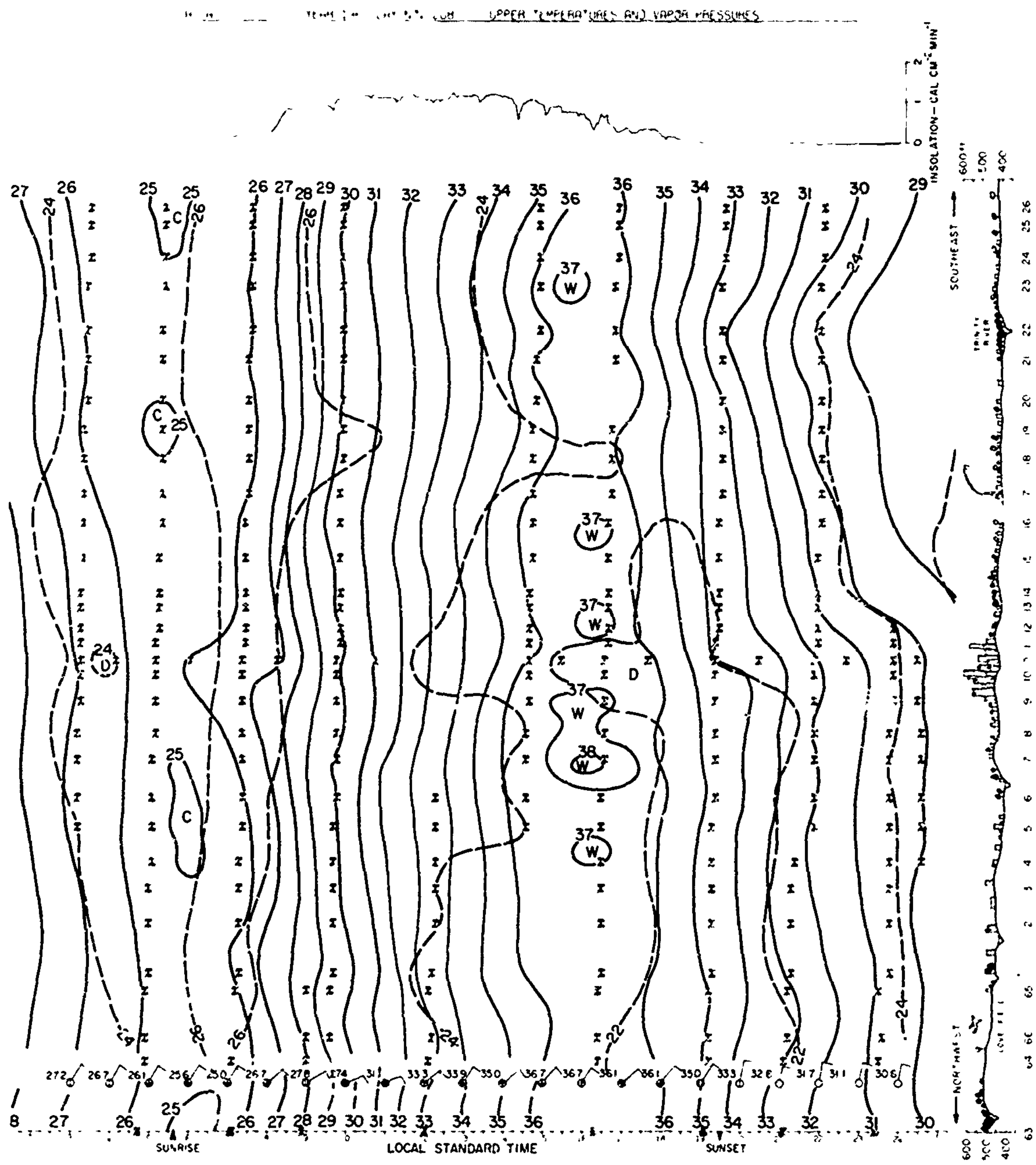
UPPER TEMPERATURES AND VAPOR PRESSURES
INSOLATION—CAL CM⁻² MIN⁻¹
SOUTHEAST
NORTHWEST
SUNRISE
LOCAL STANDARD TIME
SUNSET

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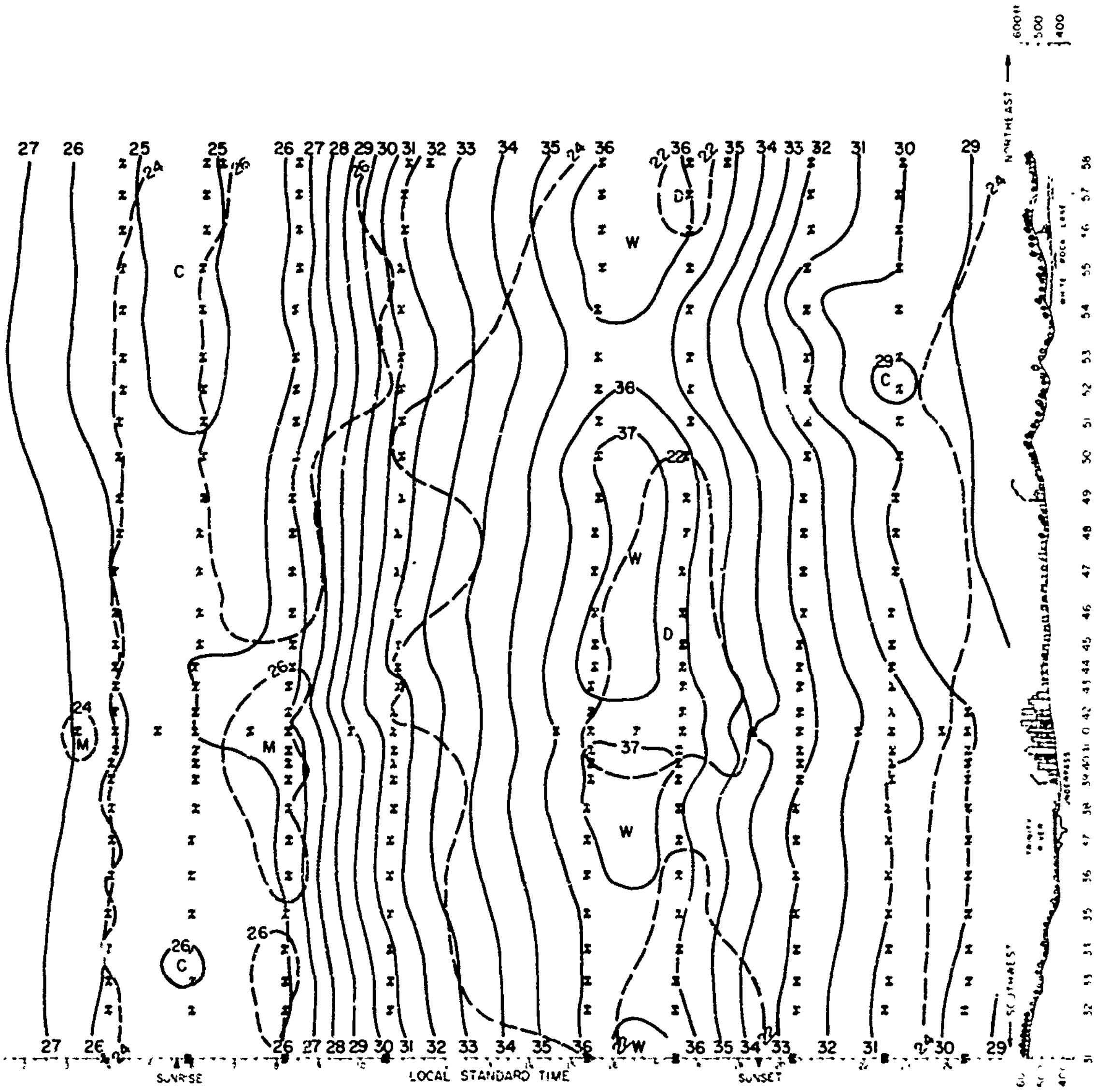

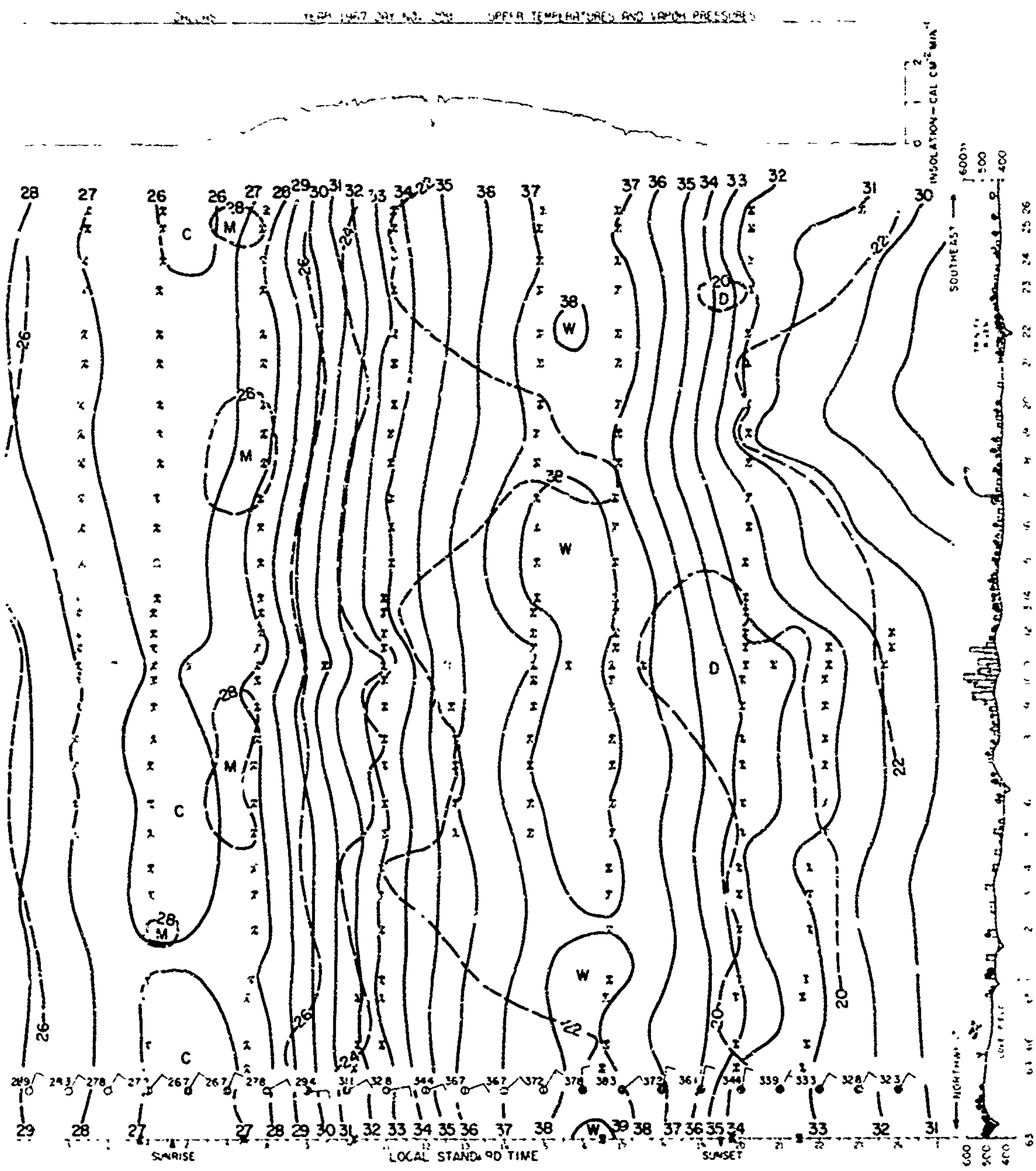
SUNRISE
LOCAL STANDARD TIME
SUNSET
SOUTHEAST
NORTHWEST

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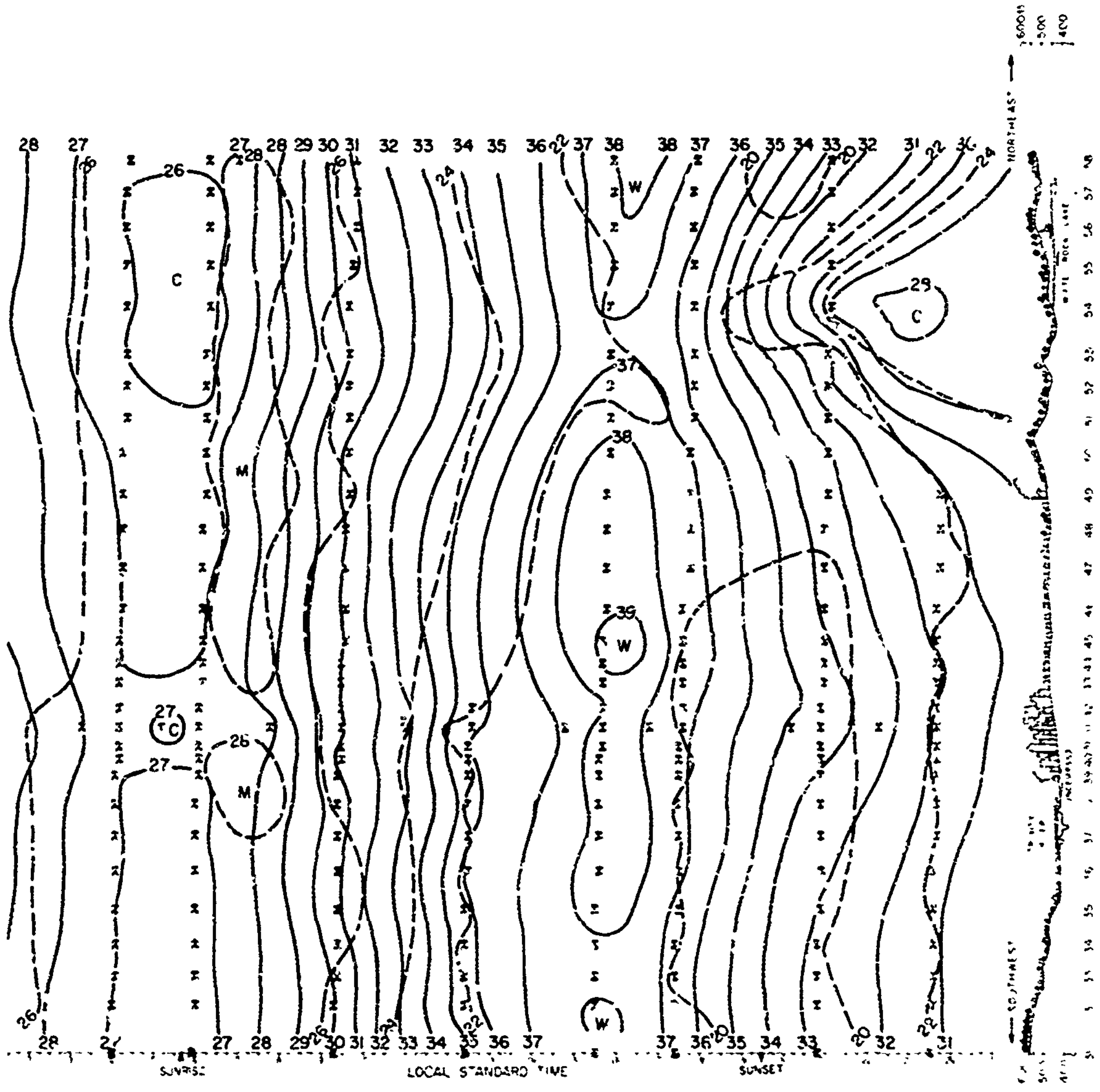
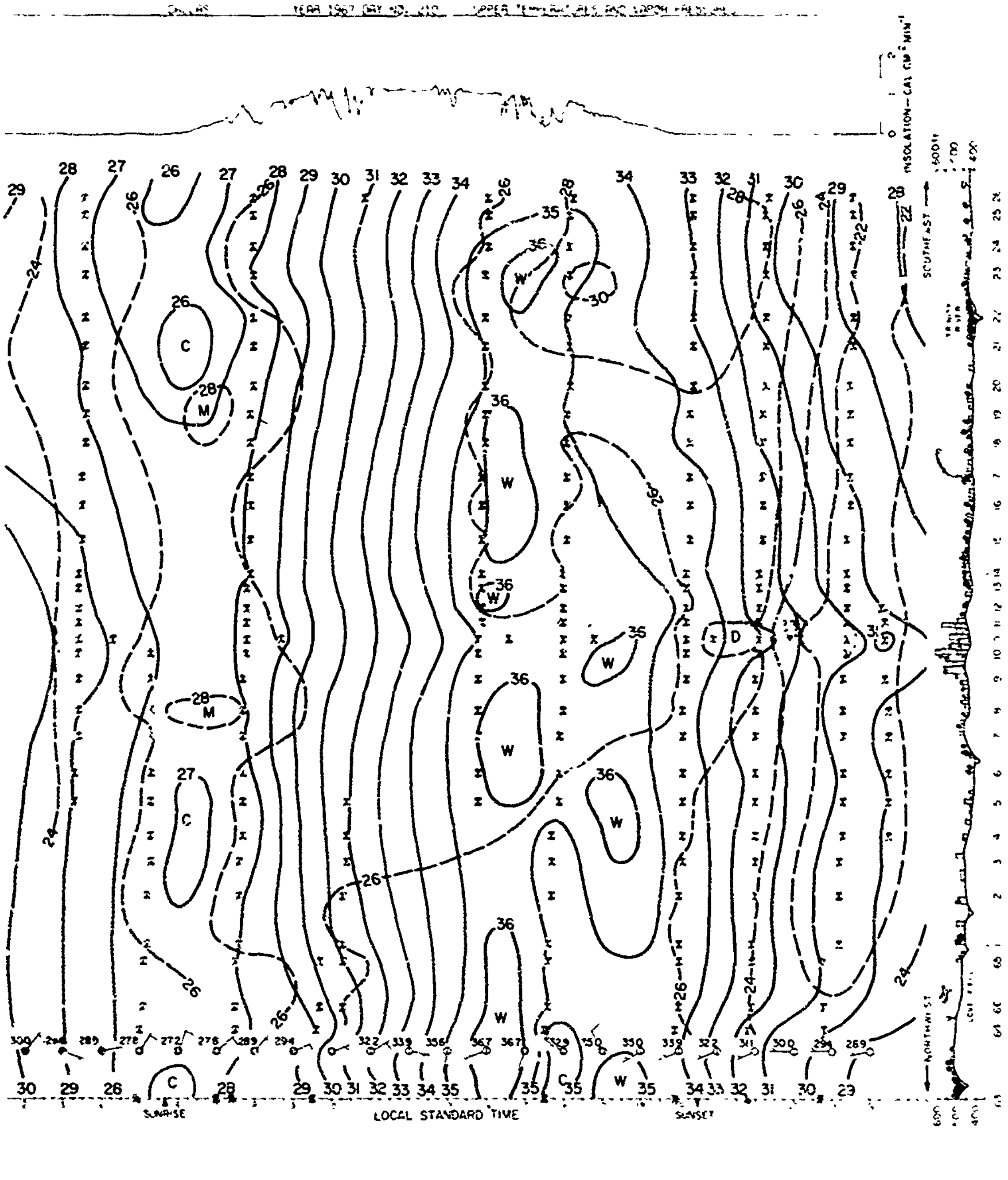
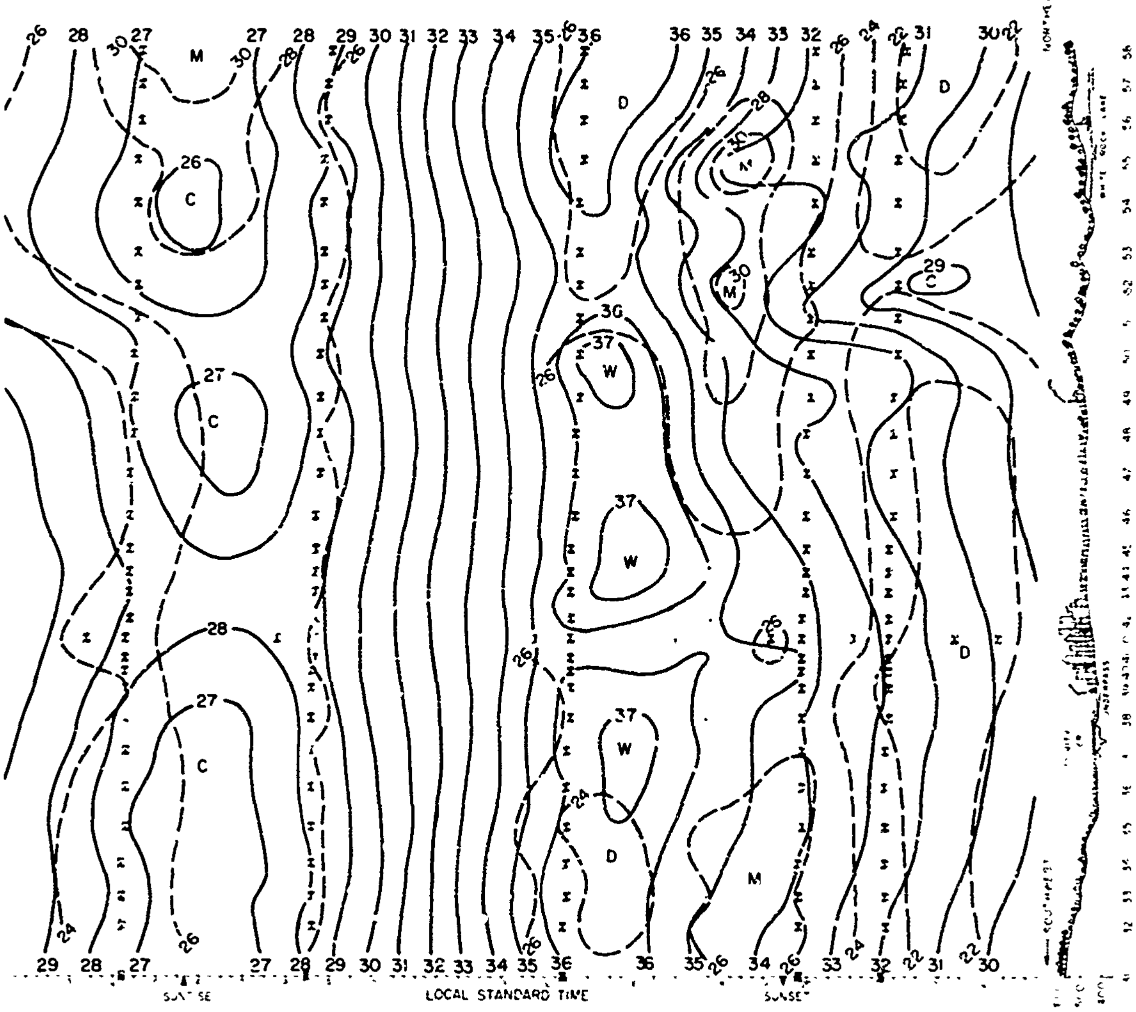
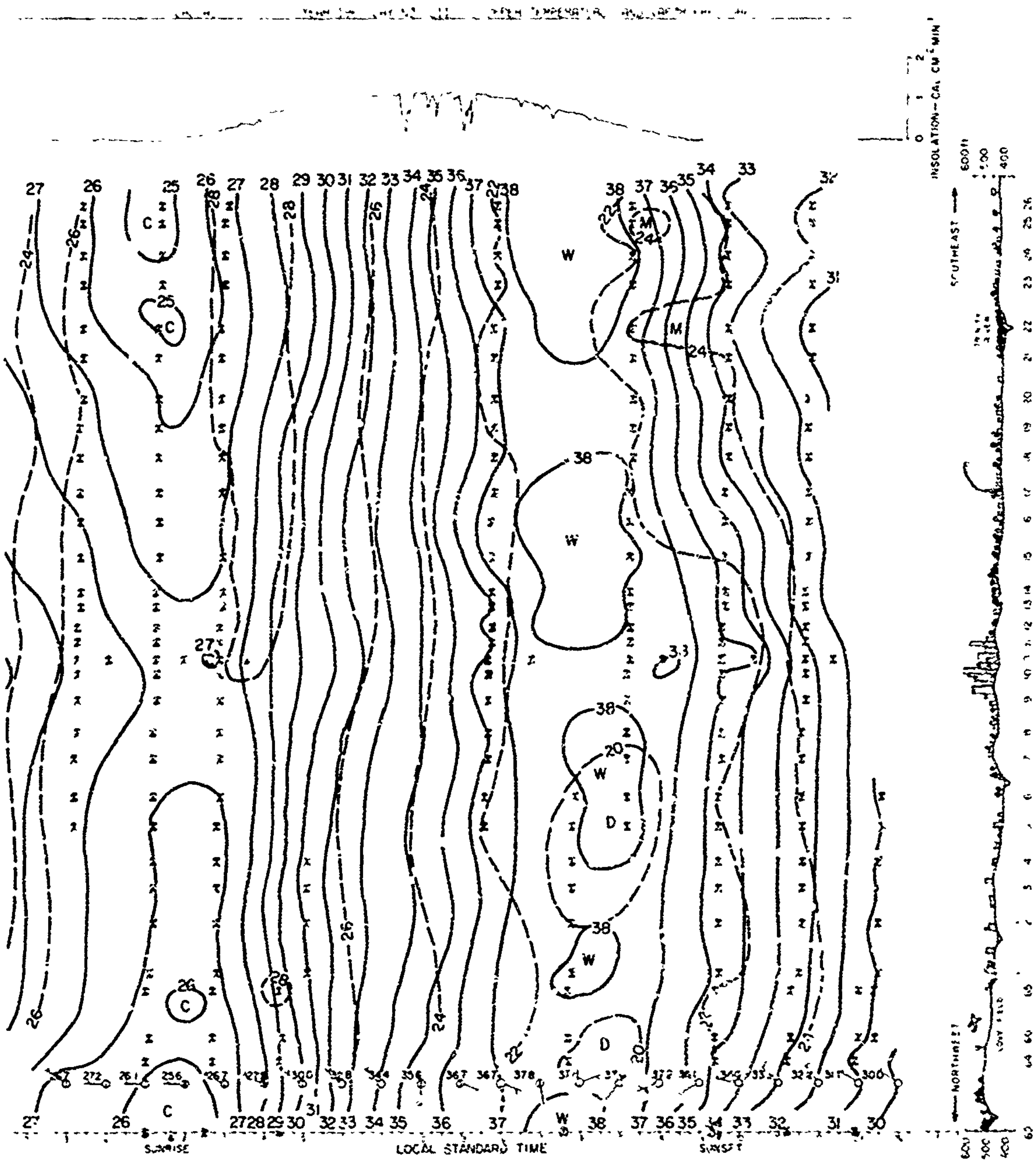




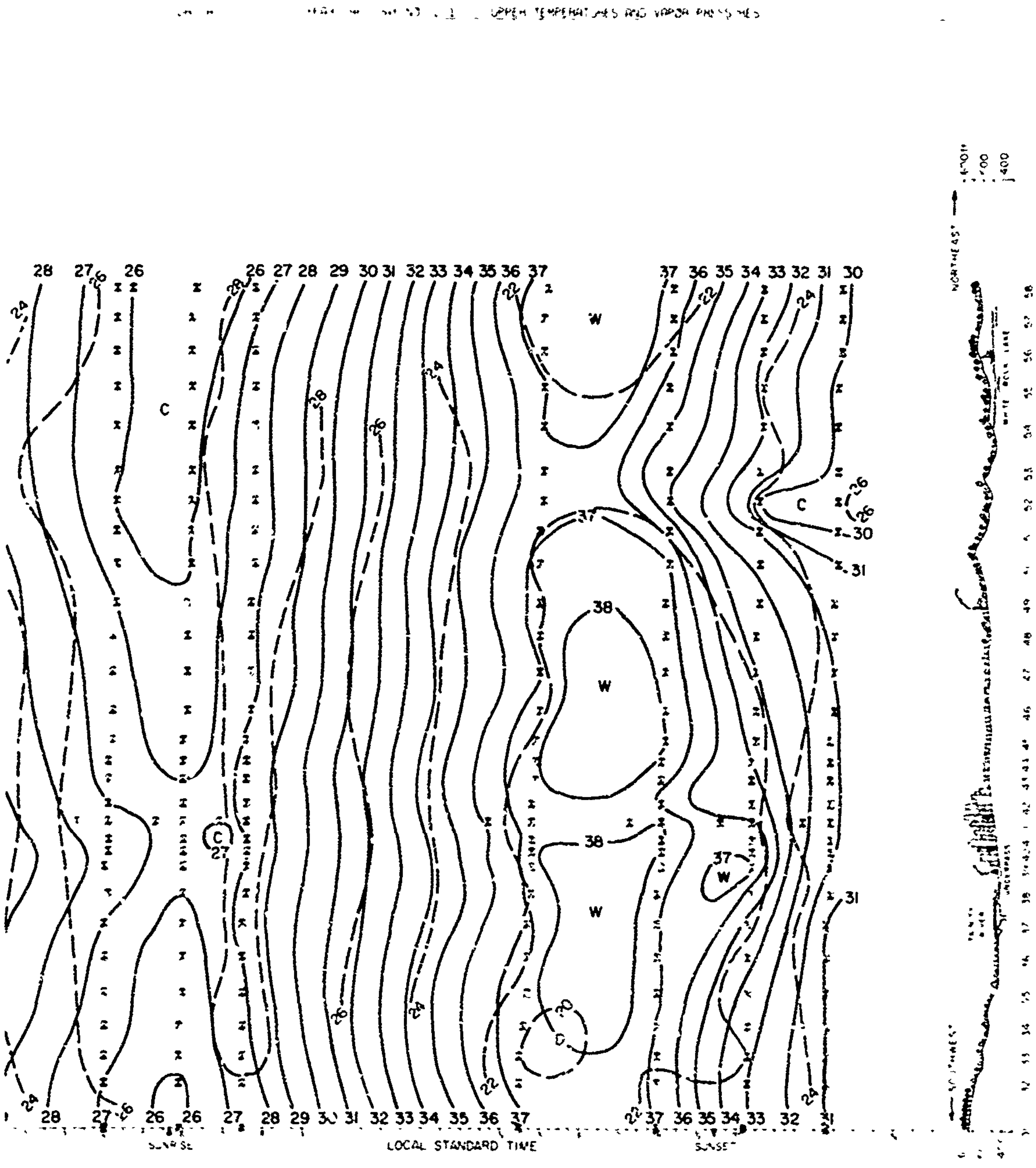
LOCAL STANDARD TIME
SUNRISE
SUNSET
INSOLATION—CAL CM⁻² MIN⁻¹
SOUTHEAST
NORTHWEST

YEAR 1957 DAY NO. 210 UPPER TEMPERATURES AND VAPOR PRESSURES

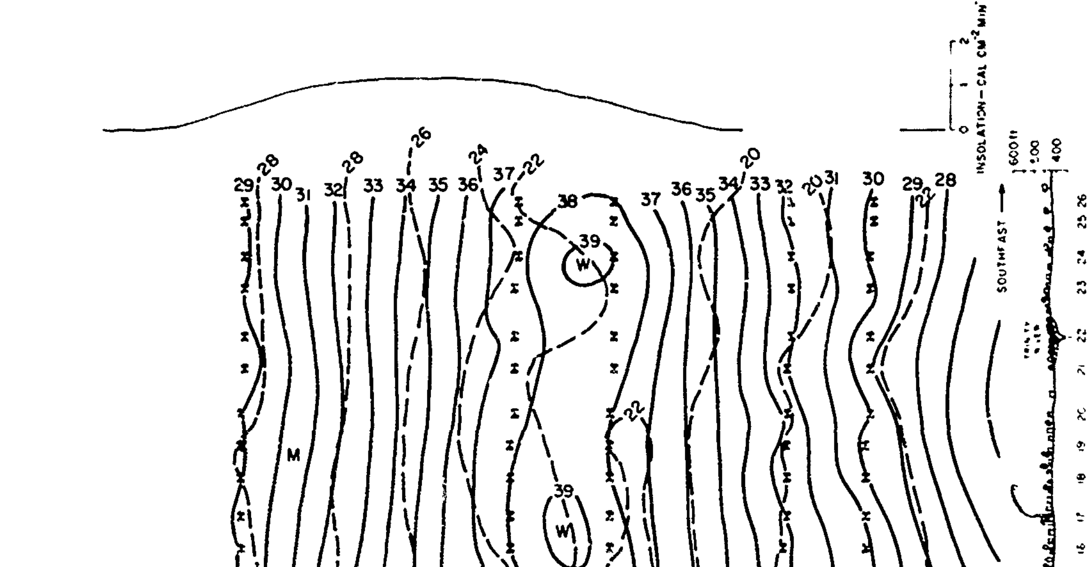


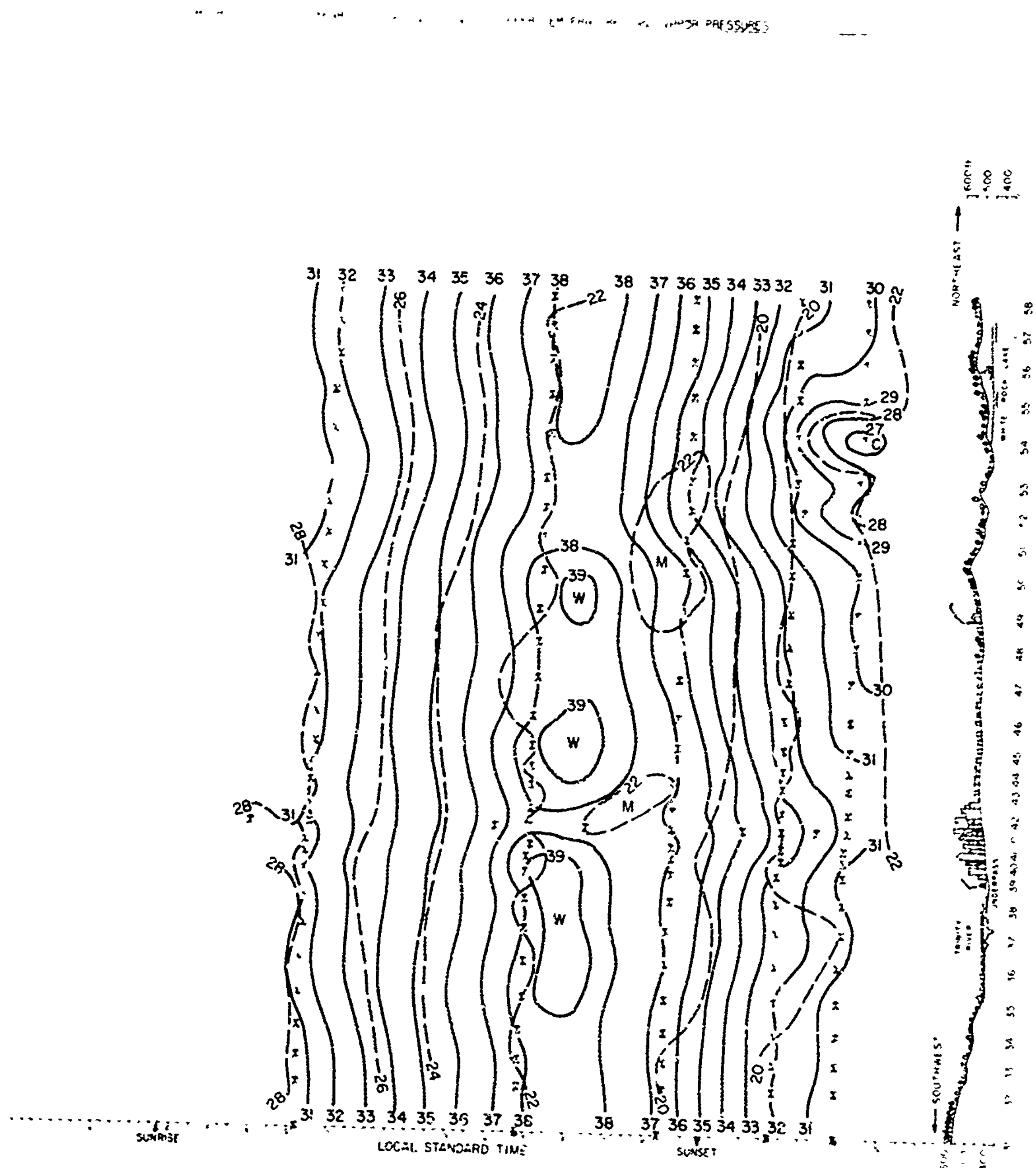


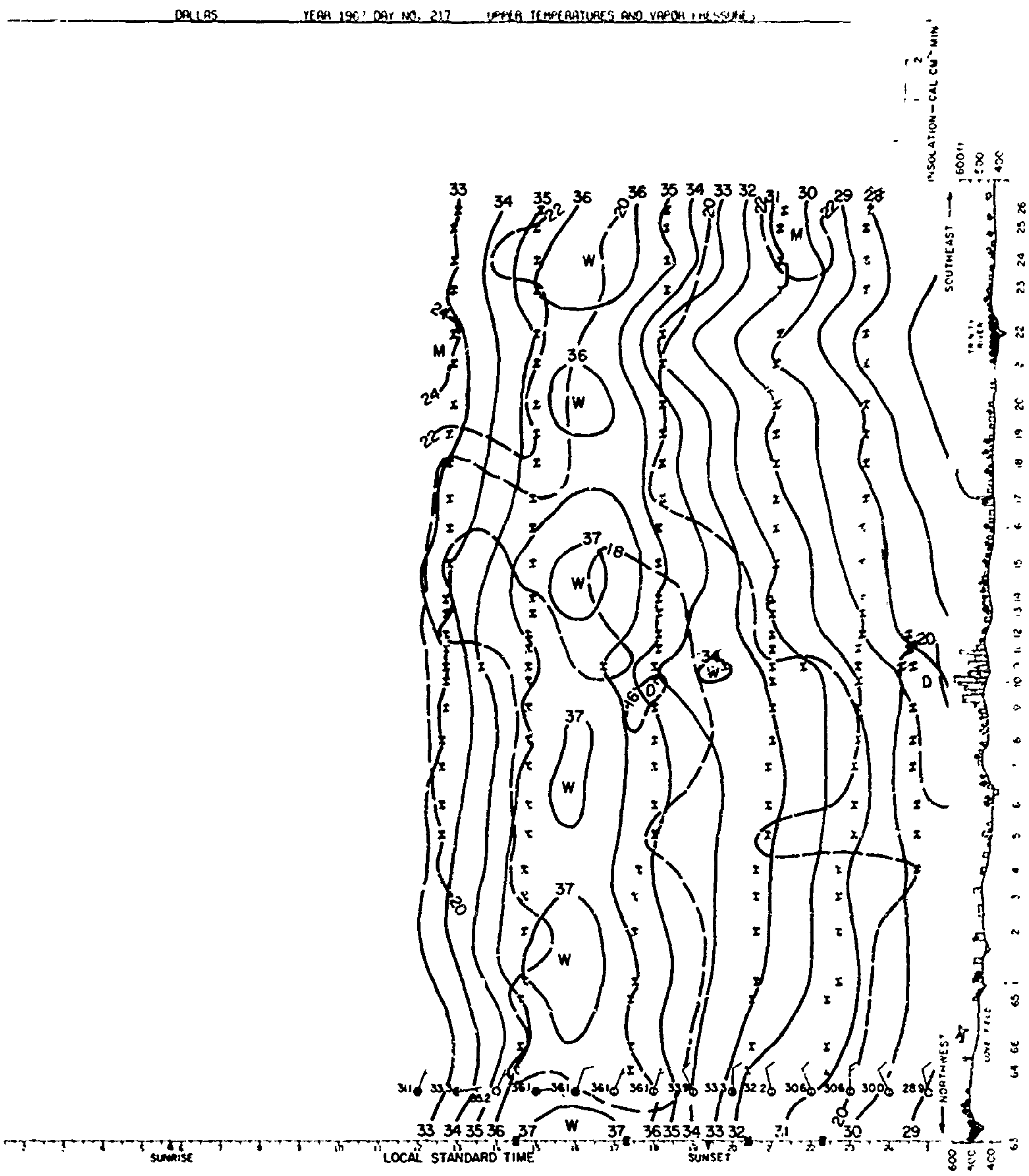
LOCAL STANDARD TIME
SUNRISE
SUNSET
INSOLATION—CAL CM⁻² MIN⁻¹
SOUTHEAST
NORTHWEST


LOCAL STANDARD TIME
SUNRISE
SUNSET
NORTHEAST
SOUTHWEST
W
C

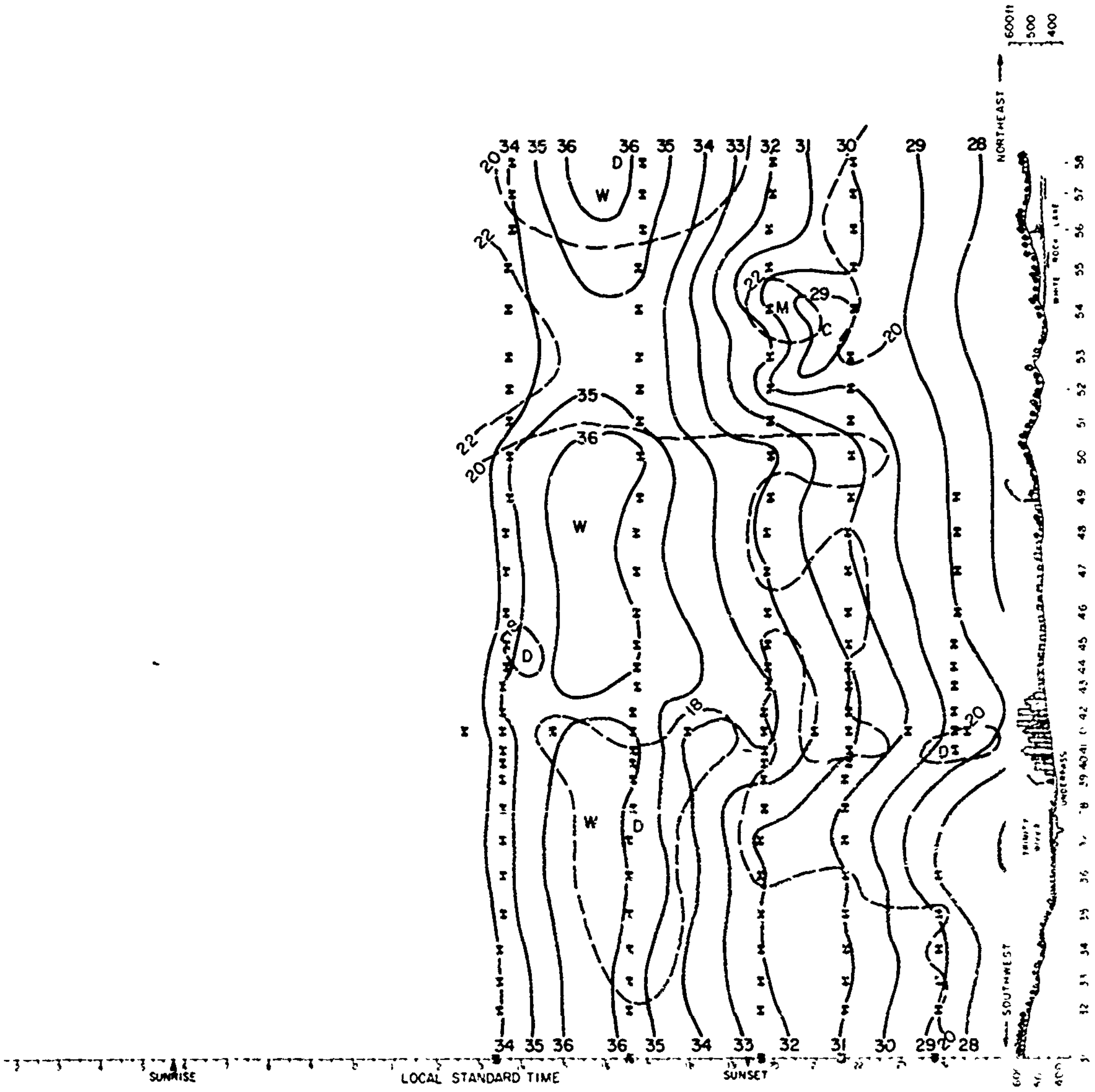
DALLAS YEAR 1967 DAY NO. 214 UPPER TEMPERATURES AND VAPOR PRESSURES

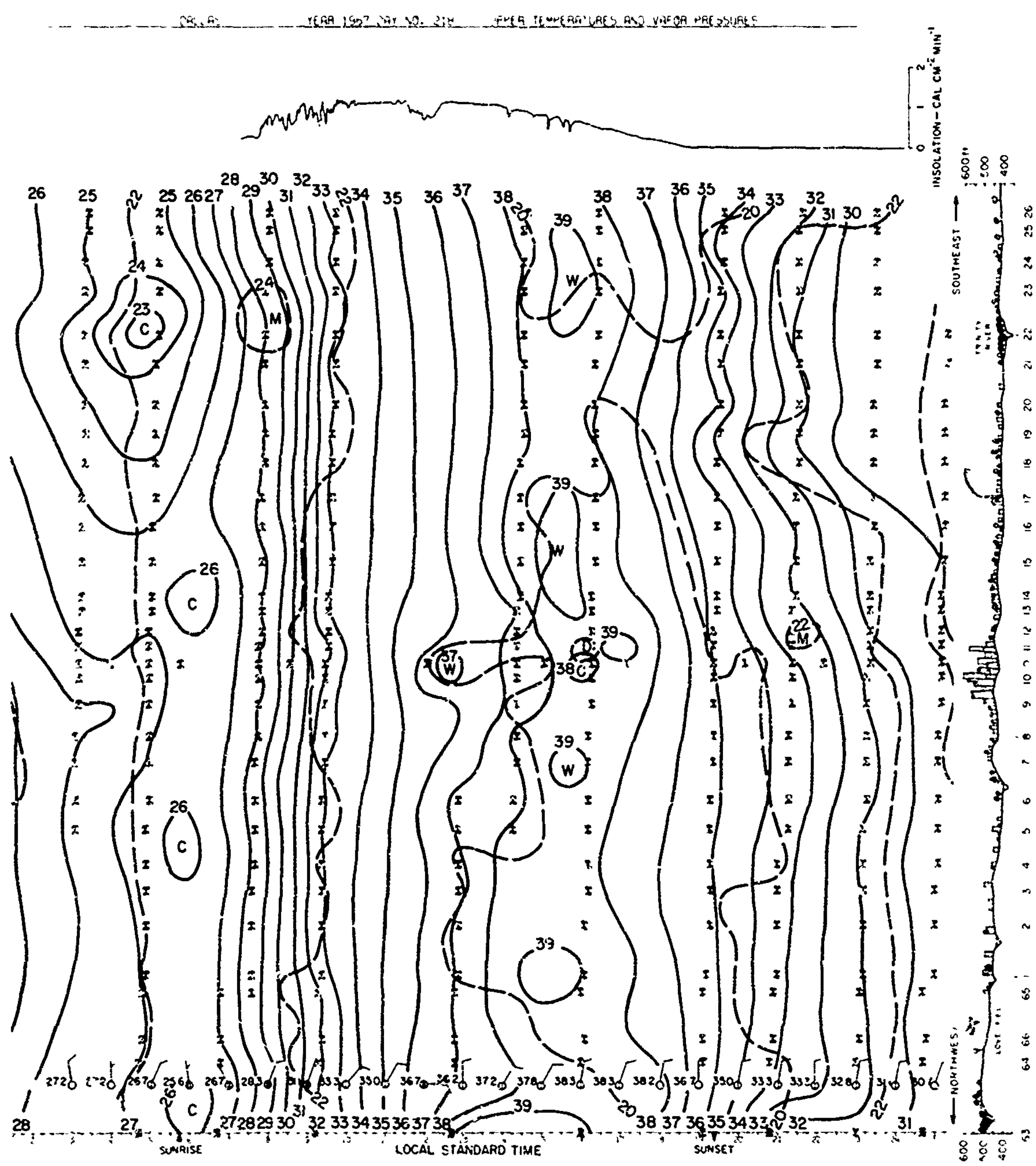


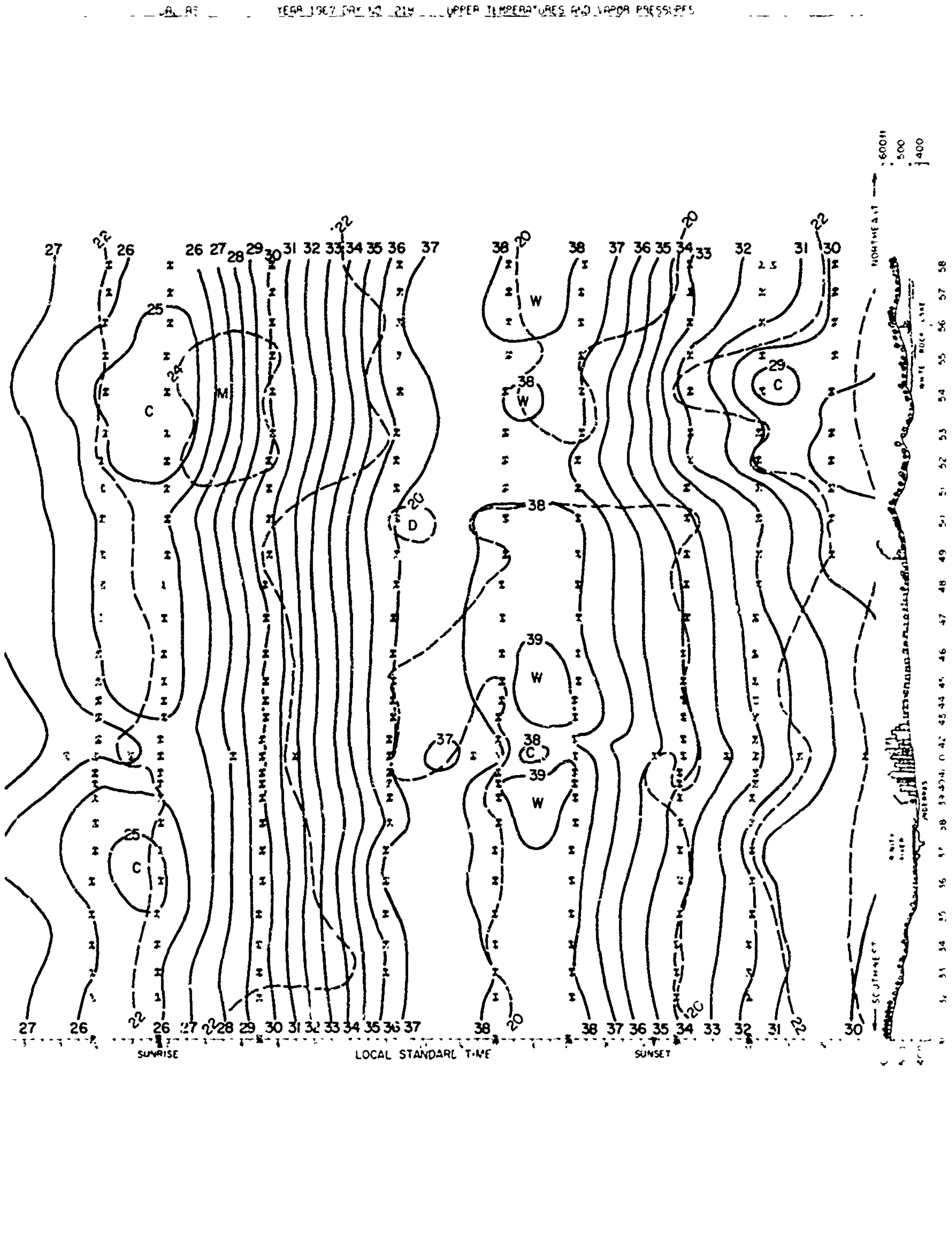

SUNRISE
LOCAL STANDARD TIME
SUNSET
NORTHEAST

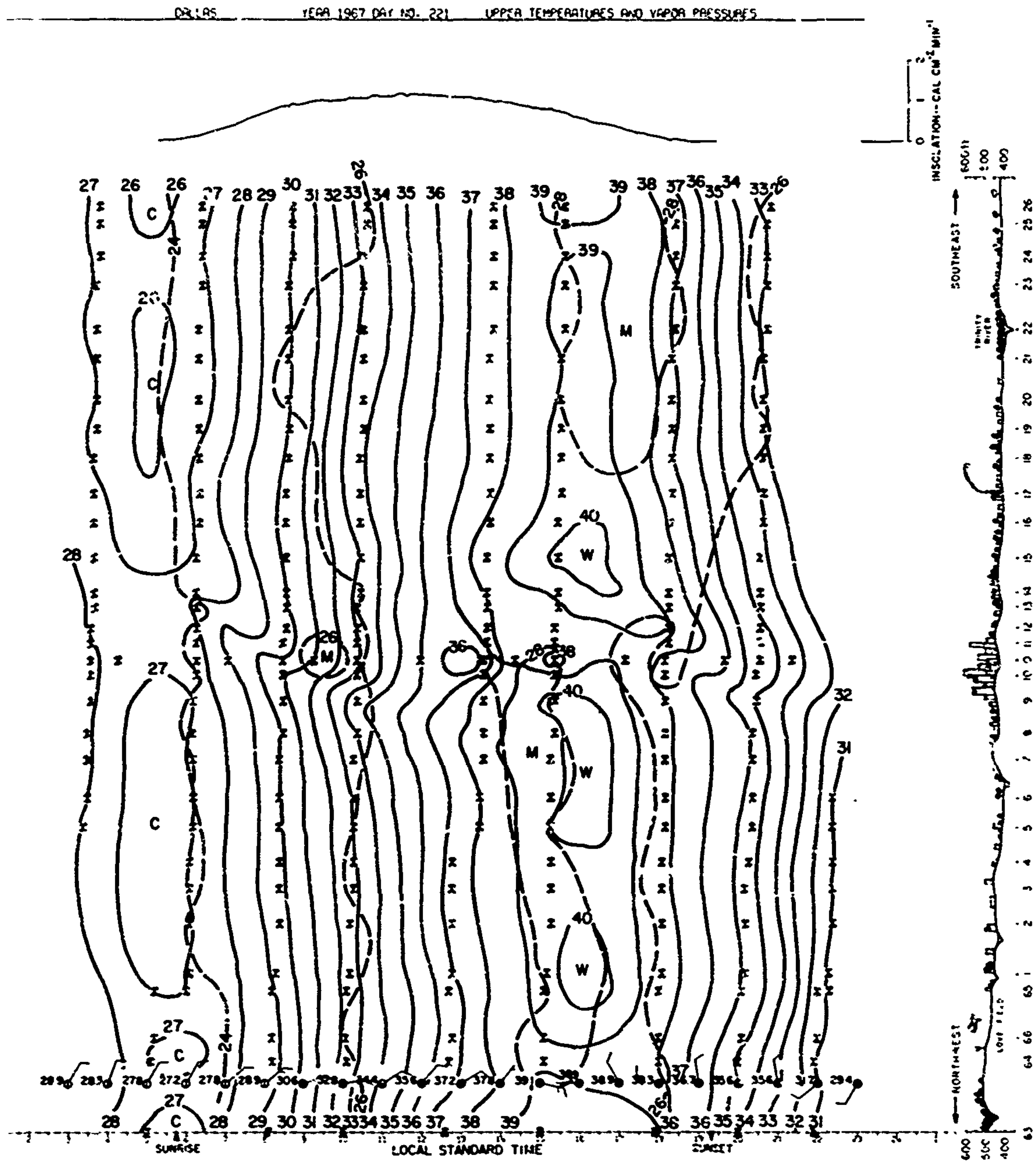

DALLAS
YEAR 1967 DAY NO. 217
UPPER TEMPERATURES AND VAPOR PRESSURES
SUNRISE
LOCAL STANDARD TIME
SUNSET
SOUTHEAST
NORTHWEST
INSOLATION—CAL CM⁻² MIN⁻¹

DALLAS YEAR 1967 DAY NO. 217 UPPER TEMPERATURES AND VAPOR PRESSURES

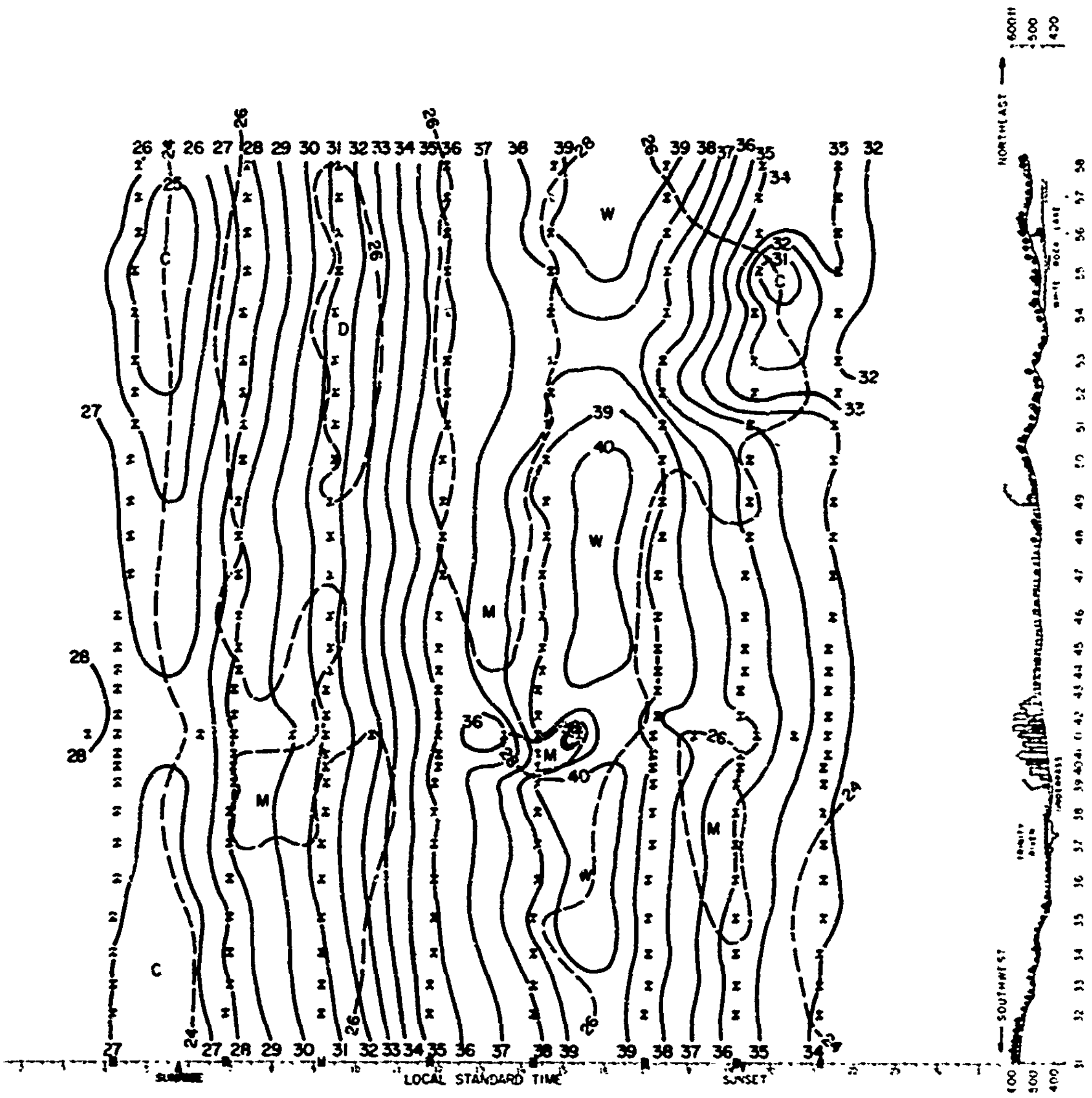



INSOLATION — CAL CM⁻² MIN⁻¹
SOUTHEAST
NORTHWEST
SUNRISE
LOCAL STANDARD TIME
SUNSET




DALLAS
YEAR 1967 DAY NO. 221
UPPER TEMPERATURES AND VAPOR PRESSURES
INSOLATION--CAL CM⁻² MIN⁻¹
SOUTHEAST
NORTHEAST
SUNRISE
LOCAL STANDARD TIME
SUNSET

DALLAS YEAR 1967 DAY NO. 221 UPPER TEMPERATURES AND VAPOR PRESSURES



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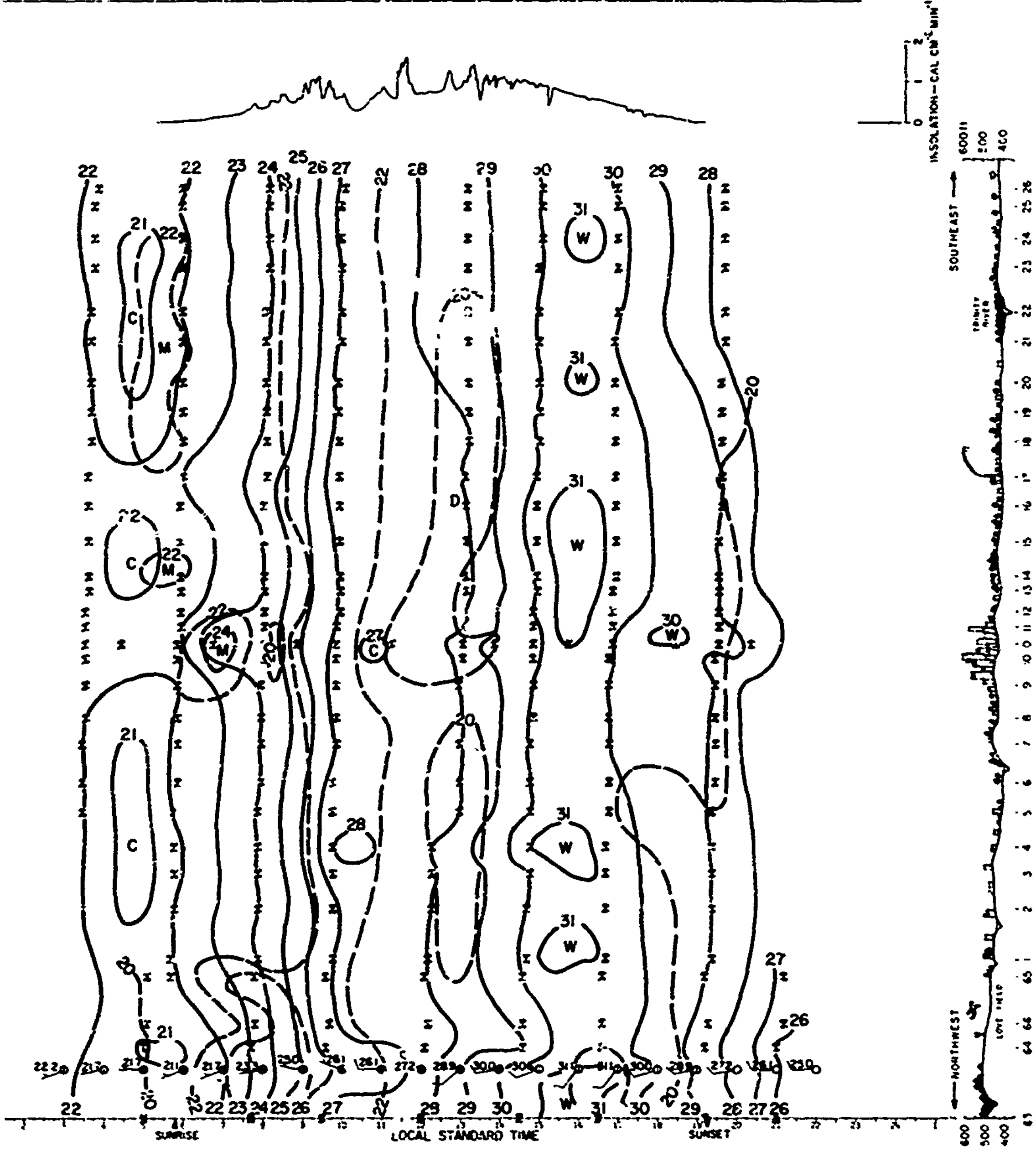

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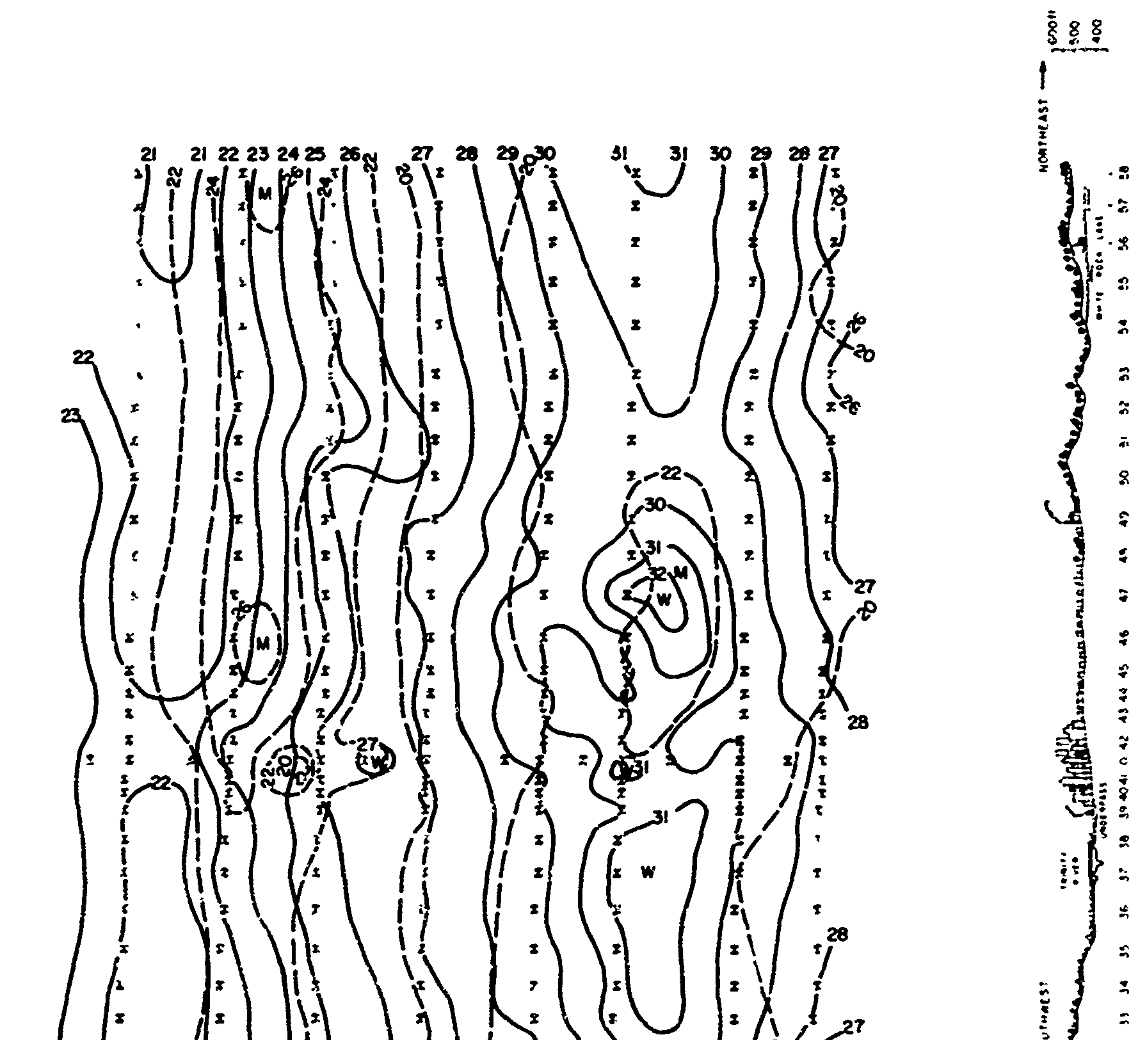
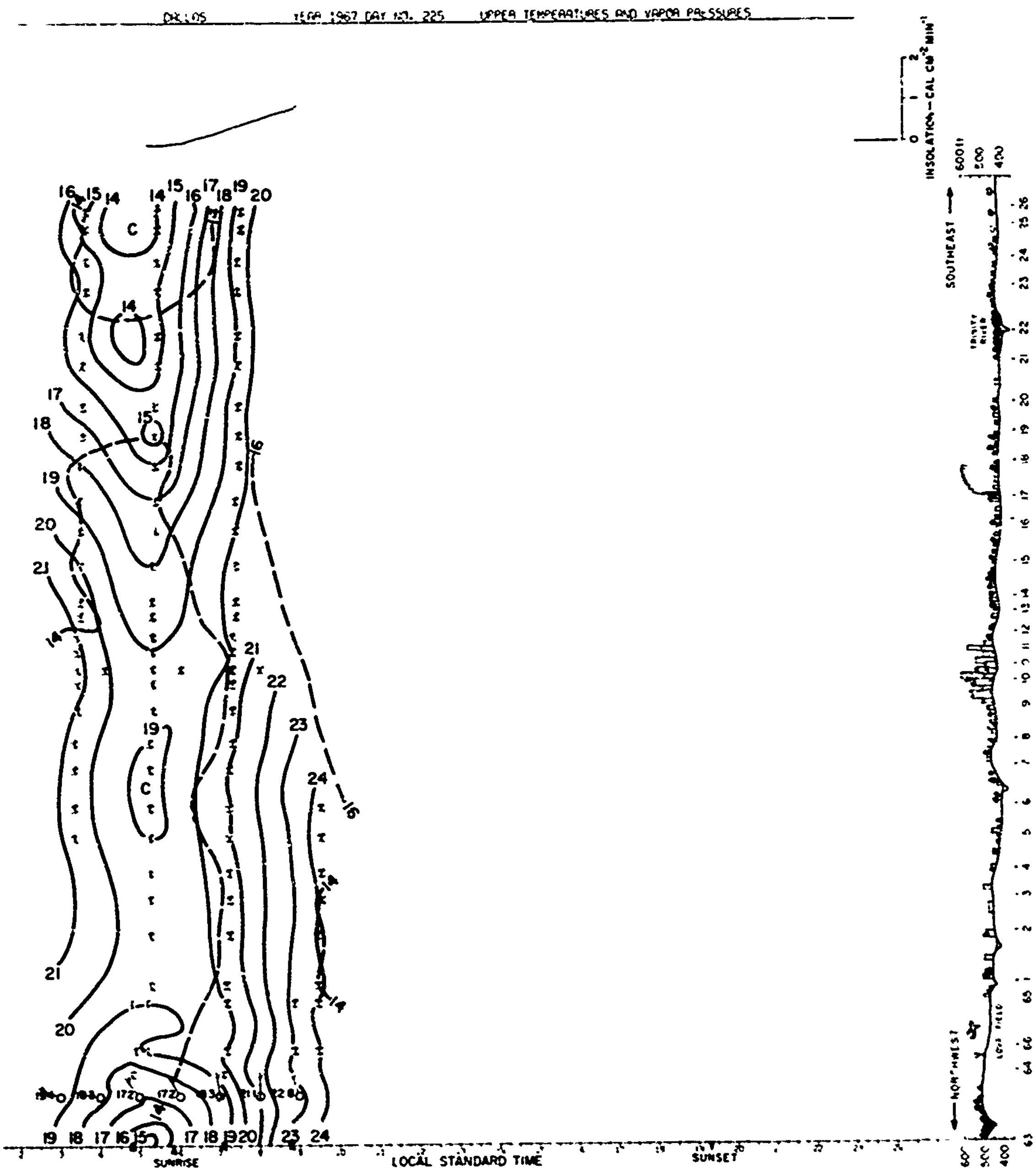
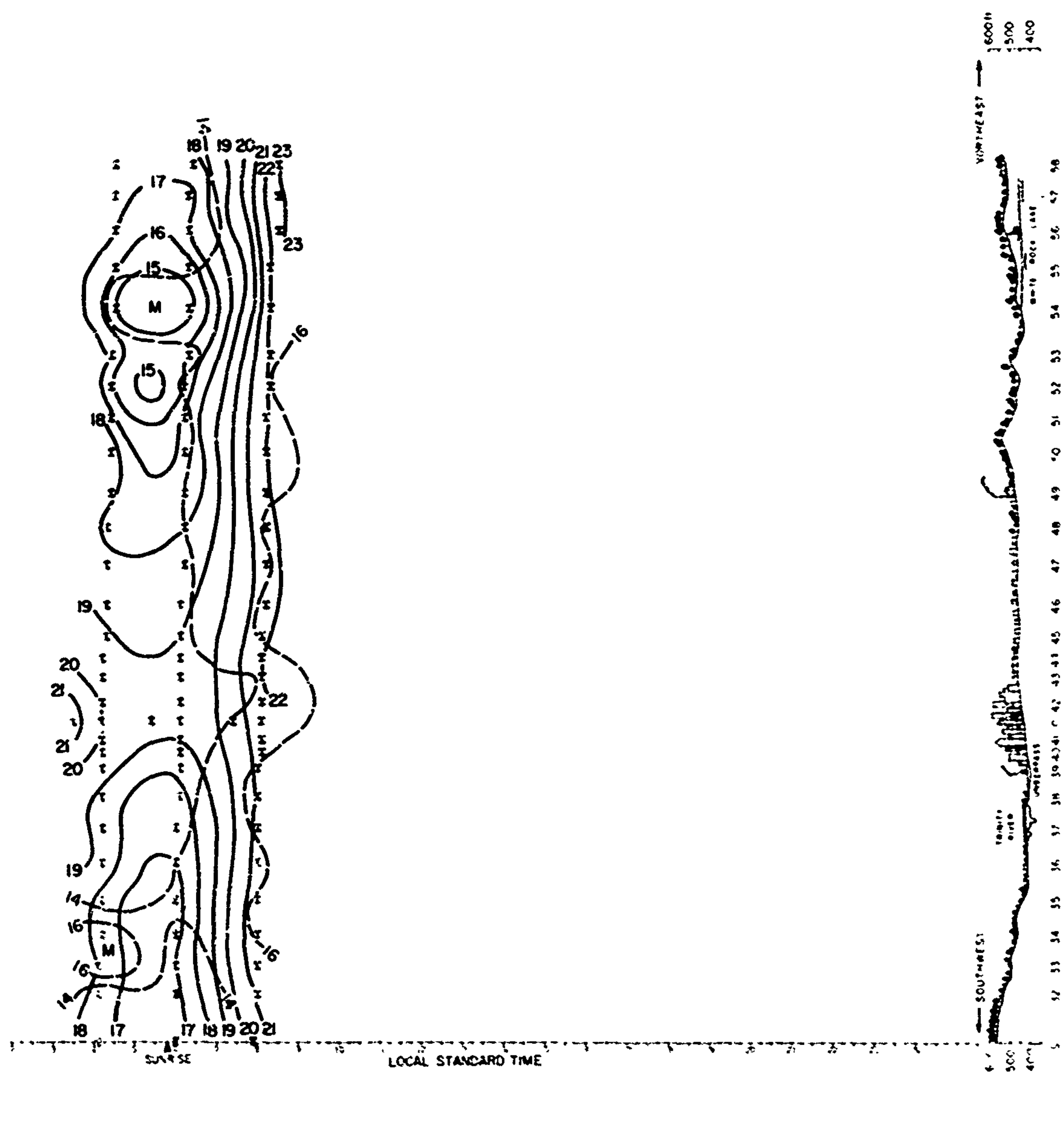


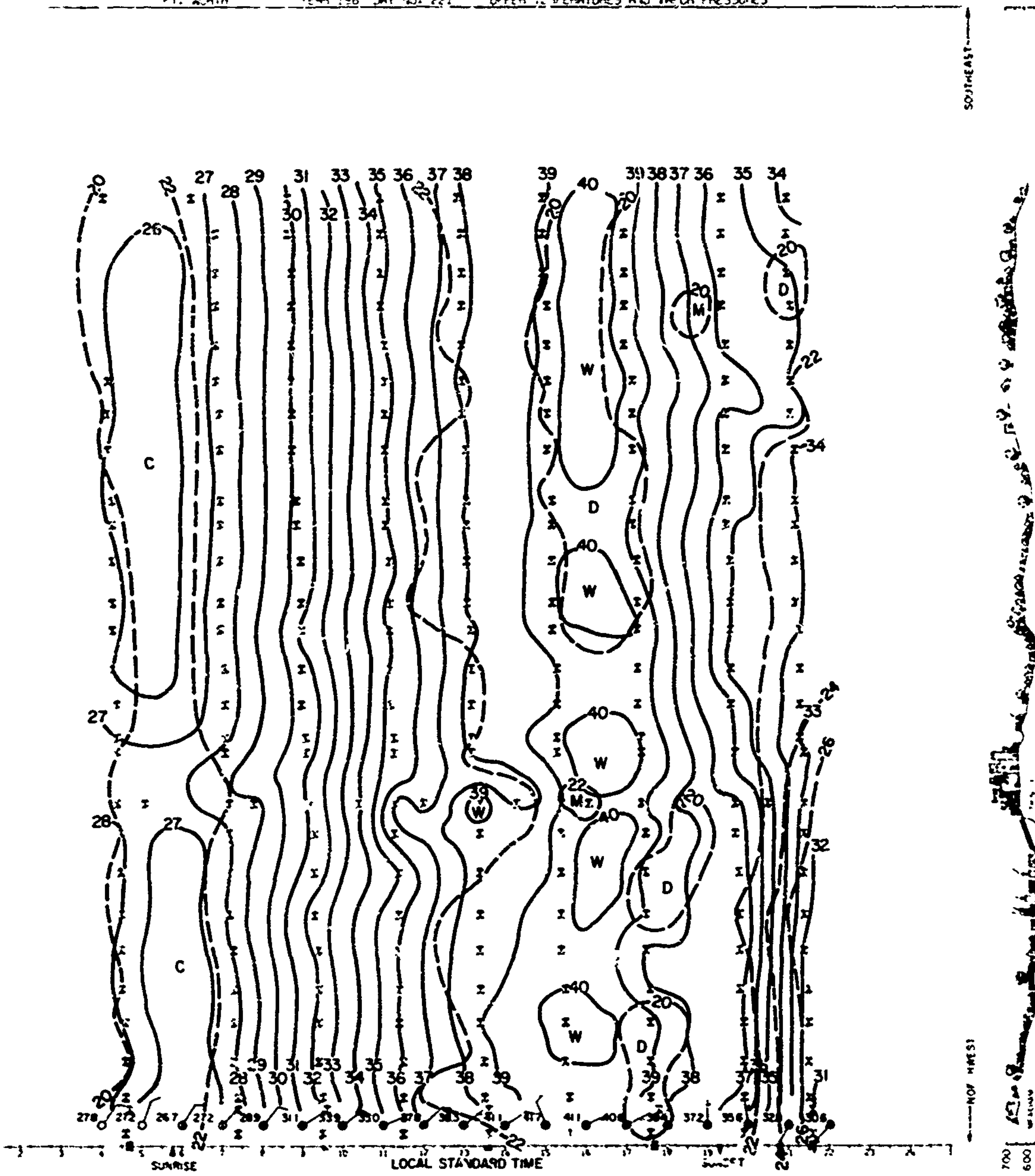


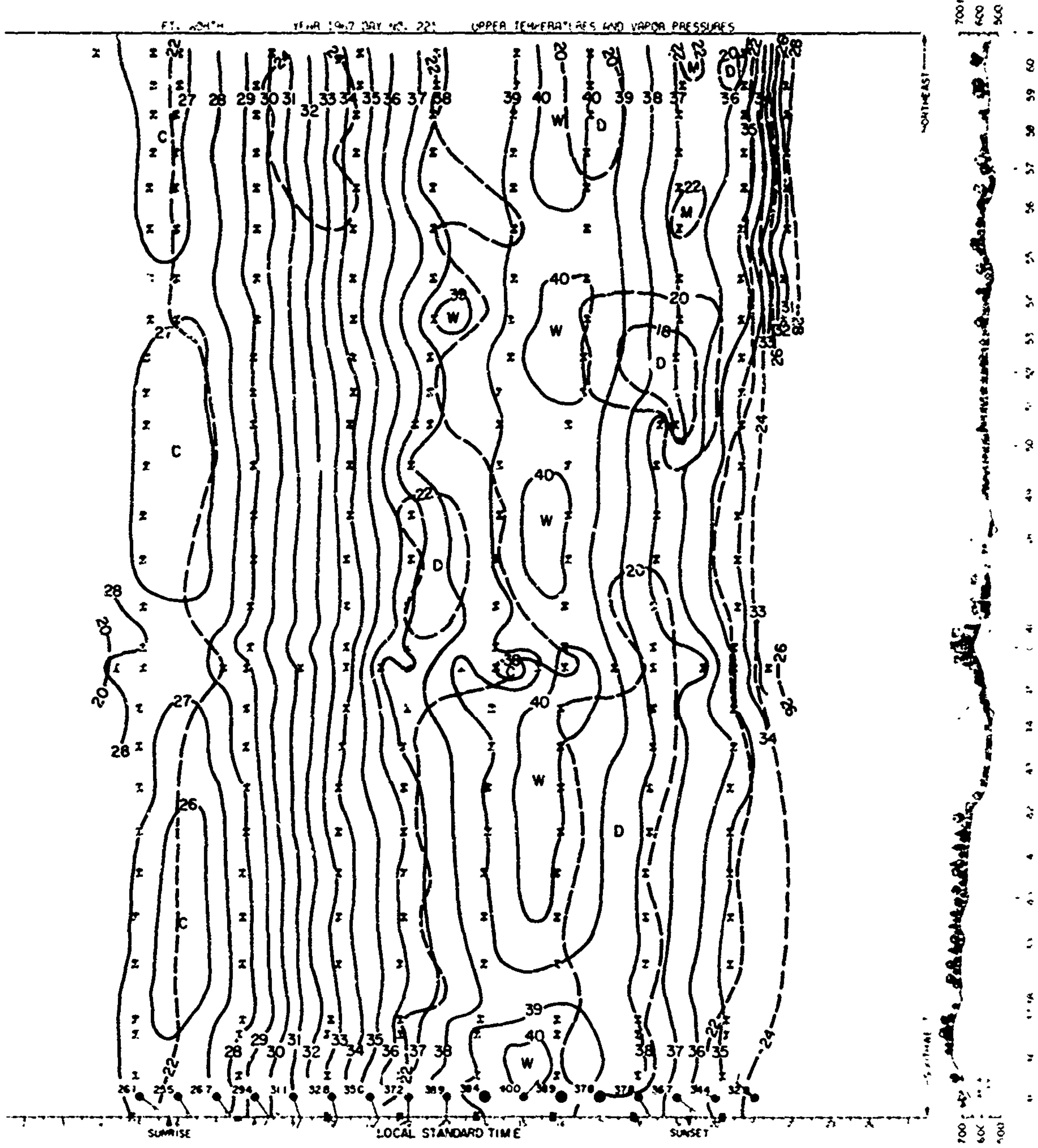
DALLAS YEAR 1967 DAY NO. 225 UPPER TEMPERATURES AND VAPOR PRESSURES
INSOLATION—CAL CM-2 MIN-1
SOUTHEAST
NORTHWEST
SUNRISE
LOCAL STANDARD TIME
SUNSET

YEAR 1957 DAY NO. 225 UPPER TEMPERATURES AND VAPOR PRESSURES

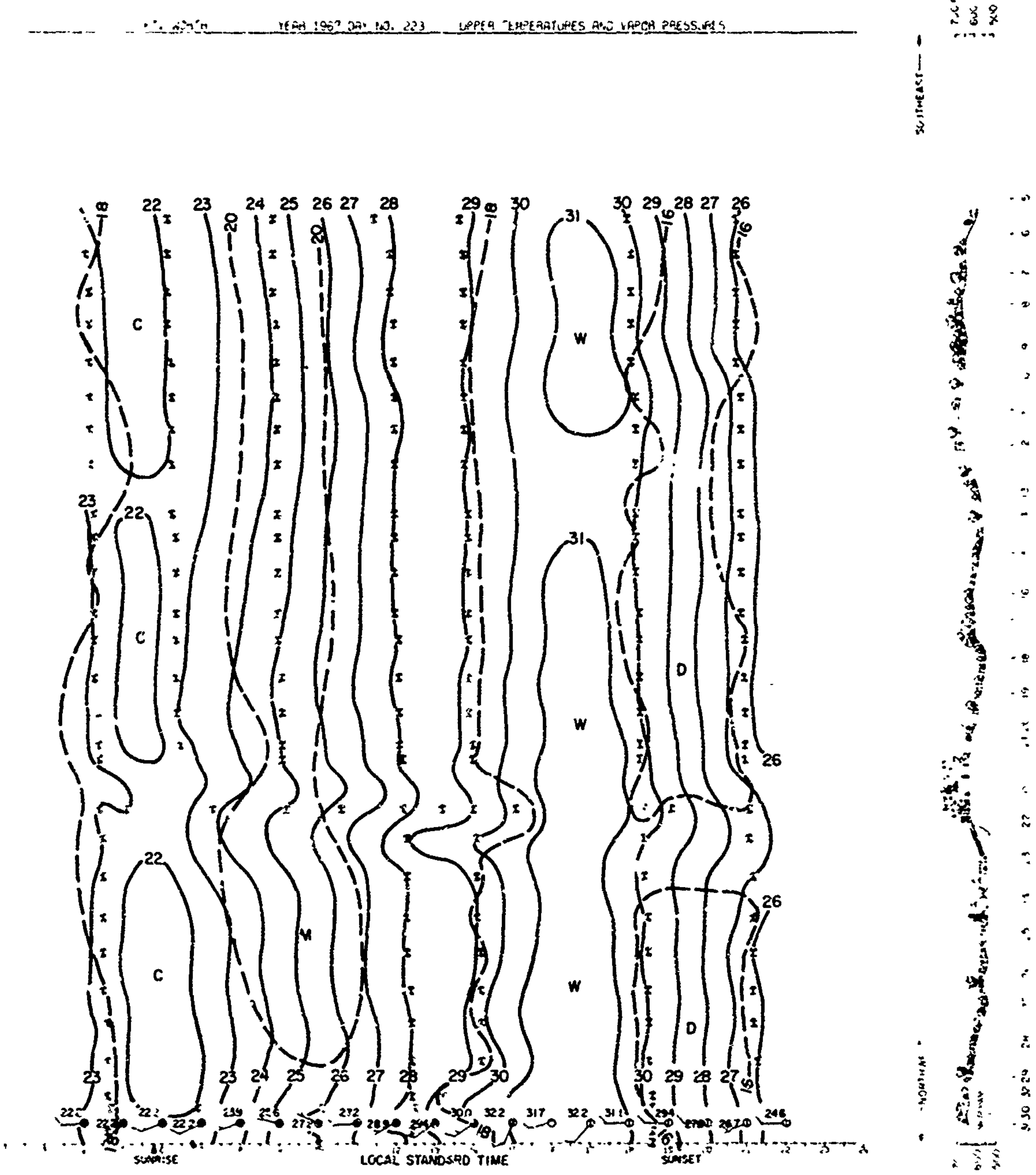


FT. WORTH YEAR 1967 DAY NO. 221 UPPER TEMPERATURES AND VAPOR PRESSURES





SUNRISE
LOCAL STANDARD TIME
SUNSET


YEAR 1967 DAY NO. 223 UPPER TEMPERATURES AND VAPOR PRESSURES
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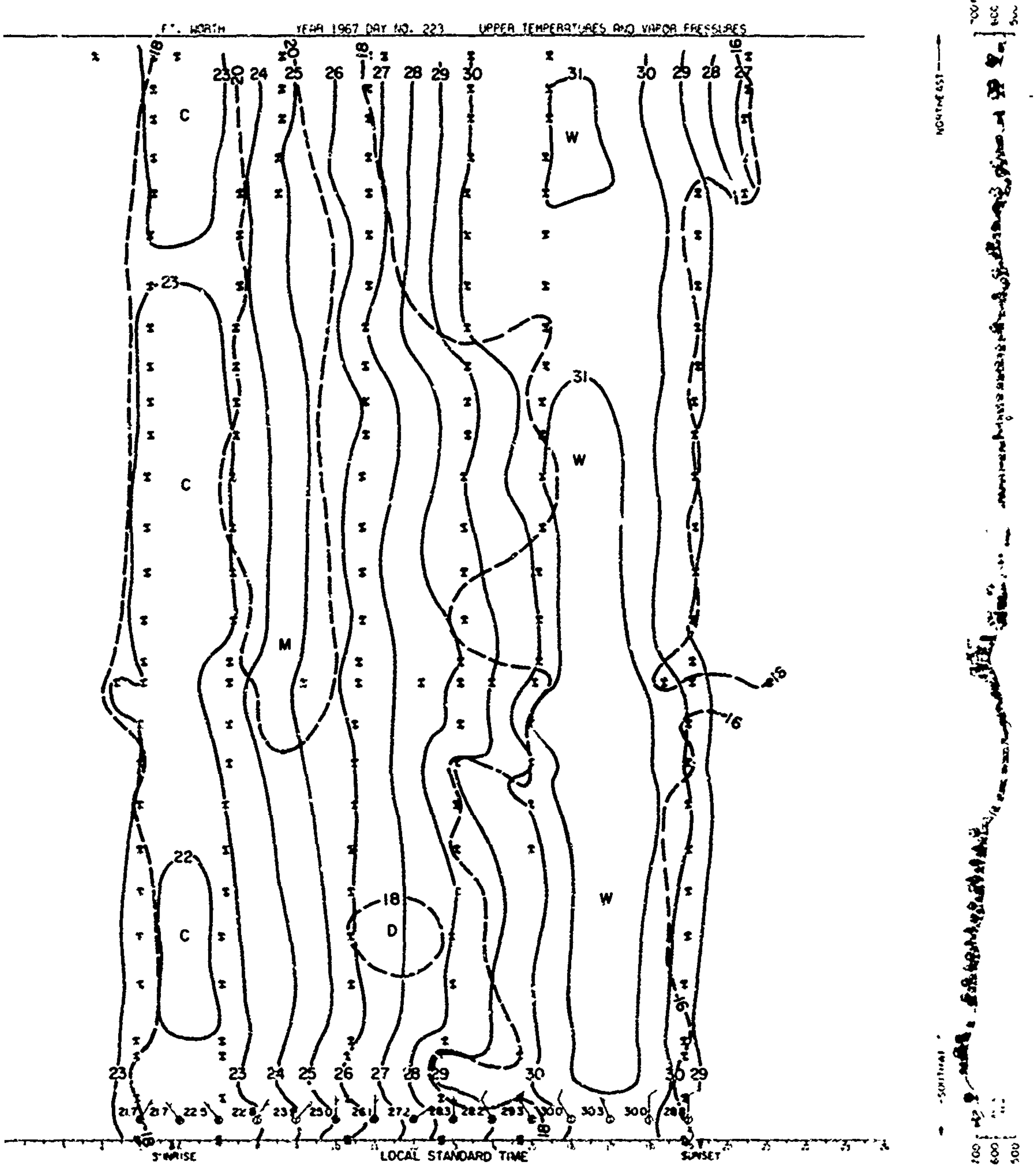
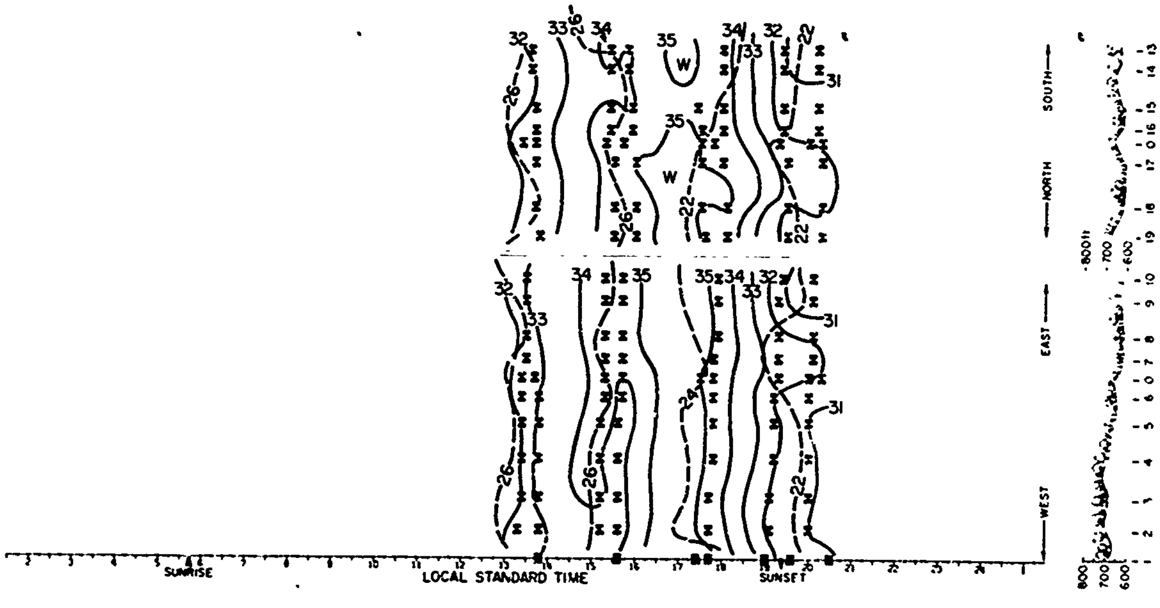
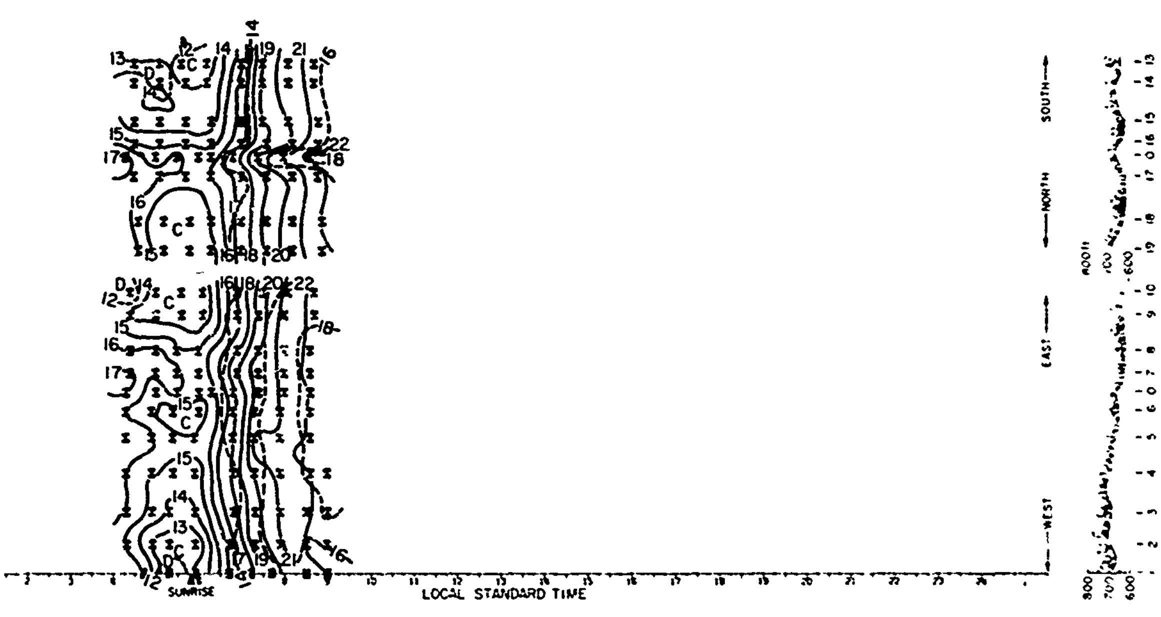
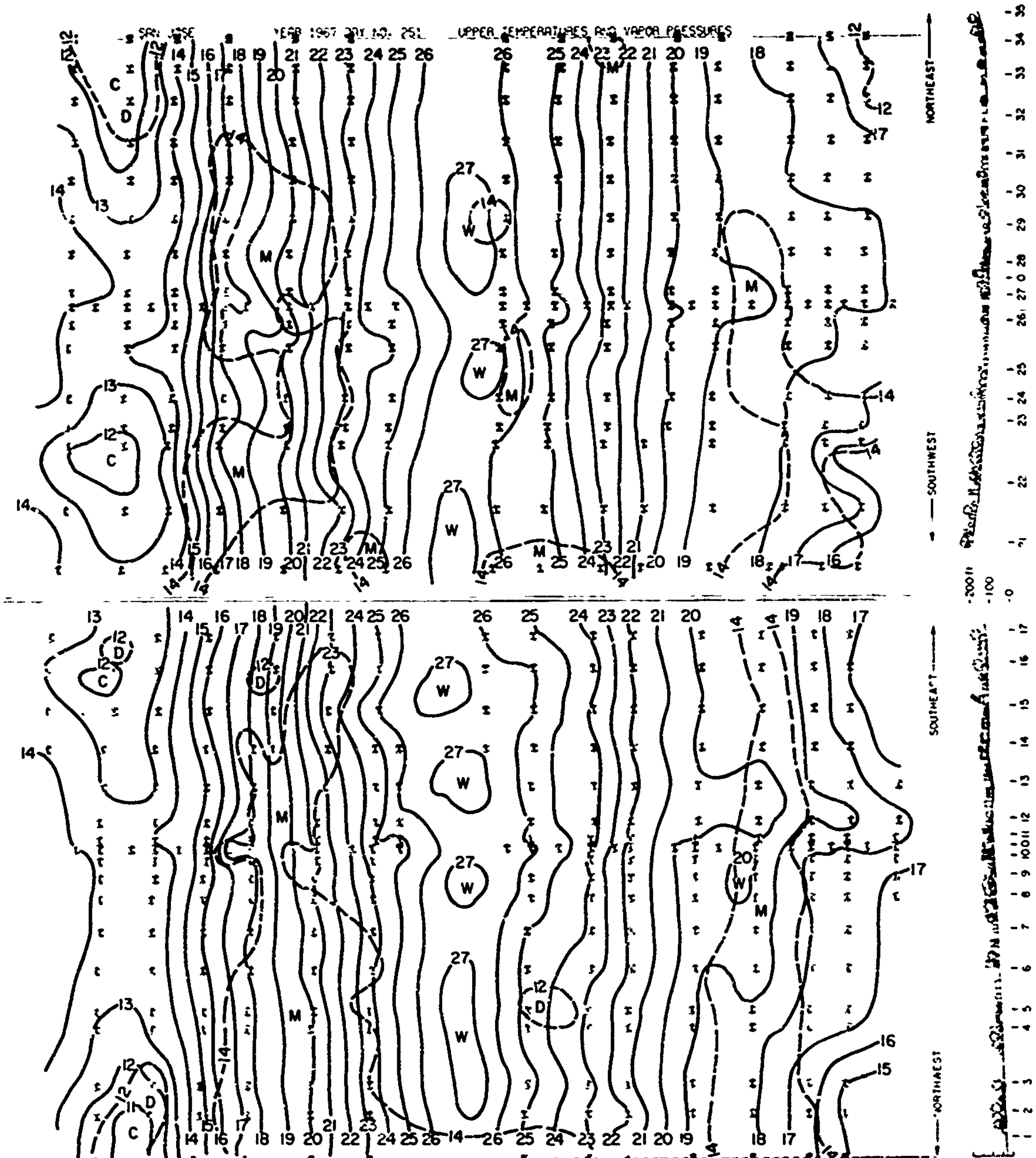

FT. WORTH
YEAR 1967 DAY NO. 223
UPPER TEMPERATURES AND VAPOR PRESSURES
SUNRISE
LOCAL STANDARD TIME
SUNSET
NORTHEAST
SOUTHWEST

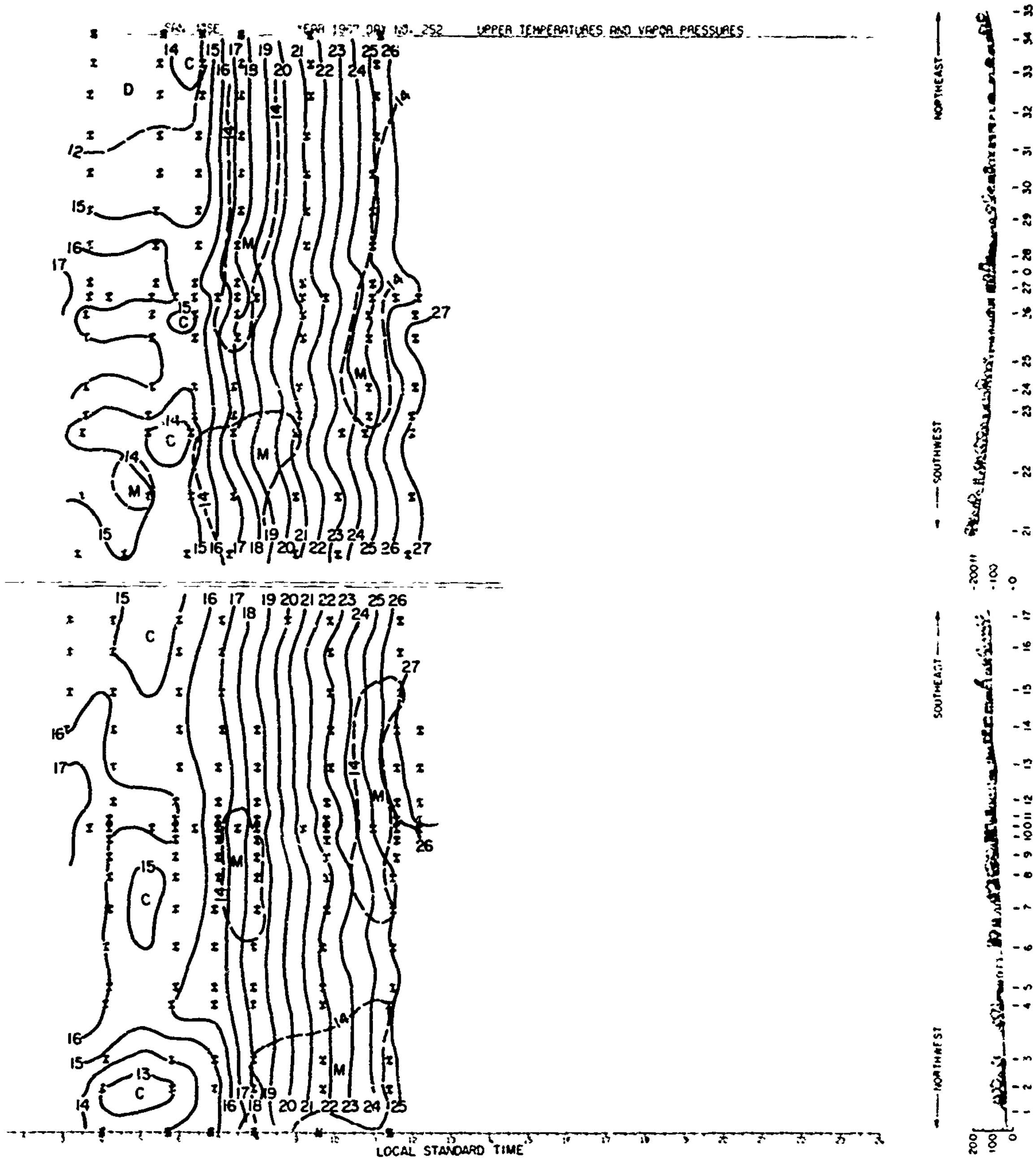
DENTON YEAR 1967 DAY NO. 217 UPPER TEMPERATURES AND VAPOR PRESSURES



DENTON YEAR 1967 DAY NO. 225 UPPER TEMPERATURES AND VAPOR PRESSURES




SAN JOSE YEAR 1967 DAY NO. 251 UPPER TEMPERATURES AND VAPOR PRESSURES
NORTHEAST
SOUTHWEST
SOUTHEAST
NORTHEAST
LOCAL STANDARD TIME


UPPER TEMPERATURES AND VAPOR PRESSURES
LOCAL STANDARD TIME
NORTHEAST
SOUTHWEST
SOUTHEAST
NORTHWEST

Appendix C

SUMMARY OF PROCESSES AFFECTING URBAN TEMPERATURE AND HUMIDITY FIELDS

Appendix C

SUMMARY OF PROCESSES AFFECTING URBAN TEMPERATURE AND HUMIDITY FIELDS

This Appendix has been included for those readers who have non-meteorological backgrounds. Much of the material included here is not new; it has been compiled from a very large number of sources. For simplicity, we discuss temperature and humidity in separate sections, but within each section we have attempted to follow the same general lines of explanation. We begin with brief explanations of the fundamental processes which transfer heat (or water vapor) and thus alter the temperature (or humidity) fields. We also discuss the measurement process and how this affects the values we obtain. From here it is an easy step to a discussion of the city and its effects on the fundamental processes, and from there to a deduction of how the temperature or humidity fields might be affected.

A. Temperature

1. Energy Transfer Processes

a. Radiation

Energy from the sun comes to the earth as electromagnetic radiation of mainly short wavelengths while the earth radiates energy to space in the longer wavelengths. Ninety-nine percent of the incoming solar radiation is at wavelengths shorter than 4 μ (with the greatest amount in the visible), and ninety-nine percent of the earth's radiation is between 4 and 120 μ in the infrared (Munn, 1966). Therefore, it is convenient to consider the two wavelength ranges separately and to use the term <u>shortwave</u> for solar radiation and <u>longwave</u> for terrestrial radiation.

When solar radiation strikes a body, the absorbed radiation is converted to heat. Absorption characteristics for a given substance are a property of that material and may vary with wavelength. Each material

has its own absorption characteristics which strongly affect the way in which it absorbs radiation. The fraction of incident radiation absorbed, absorptivity, plus the fraction reflected, reflectivity, plus the fraction transmitted adds up to one. Incident energy must undergo one of these three processes. In this discussion, transmitted radiation is ignored. This is justified because on the scale of large buildings, streets, parks, etc. radiation becomes totally absorbed at some point of penetration, adding its heat to the material. Also, most structural and natural materials are opaque. In this context, absorptivity plus reflectivity (also called albedo) account for the disposition of incident radiation. Table C-I lists shortwave absorptivity for various natural surfaces. Because bodies receive radiation from and radiate to their environment in long wavelengths, Table C-I also lists a few longwave absorptivities. At these wavelengths, absorptivity and emissivity are equal.

Table C-I

ABSORPTIVITY OF VARIOUS SURFACES
FOR SHORTWAVE AND LONGWAVE RADIATION

Surface	Absorptivity for* Shortwave Radiation (%)	Absorptivity for Longwave† (% of Blackbody Radiation)
Fresh snow cover	5-25	99.5
Old snow cover	30-60	--
Sandy soil	60-85	95
Meadows and fields	70-88	95
Densely built-up areas	75-85	--
Woods	80-95	95 (coniferous)
Dark cultivated soil	90-93	--
Water surfaces, sea	90-97	98

* After Geiger, 1965.

† After Lowry, 1967.

Water surfaces have the highest absorptivity, ranging from 90-97%, but these values hold for incident radiation within 40° of the vertical. As the angle of incidence approaches the horizontal, reflection reduces absorption. Reflection reaches 50% at an elevation angle of 10°.

Wetting a surface generally changes the reflectivity and absorptivity. Sauberer (1951) gives an example with sand:

Wavelength (μ)	Percent Radiation Absorbed	
	Dry Sand	Wet Sand
0.4	80	90
0.6	71	85
0.8	70	81

It can be seen that there is a definite increase in absorptivity as sand becomes wet.

Shortwave absorption by atmospheric gases is negligible. The heat absorbed at these wavelengths would only raise the air temperature from 0.3 to $0.6^{\circ}C$ per day depending on the amount of water vapor in the air (Berry et al., 1945). Longwave absorption in the atmosphere is dominated by water vapor, almost to the exclusion of other gases. At wavelengths greater than 14 μ absorption effectively traps half of the outgoing terrestrial radiation. The interval between 8-13 μ is a water-vapor transmission band for longwave radiation that allows emission in the region of maximum intensity. Dry air can be neglected as an absorber-emitter of radiation.

Scattering is another process that serves to alter the quantity and quality of radiation. Short wavelengths are more effectively scattered by the atmosphere than are long wavelengths. Scattering causes the shorter wavelength radiation to be more diffuse than it would be otherwise. The blueness of the sky indicates that the shorter wavelength blue light arrives from almost the whole dome of the sky, whereas longer wavelengths come more from the sun's direction only. Larger particles whose

dimensions exceed the wavelengths of solar radiation reflect light rather than scatter it. Reflection is more nearly independent of wavelength, so high particulate concentrations can cause diffuseness in the incoming radiation at the longer wavelengths. Furthermore, the larger particles can absorb incoming radiation preventing it from reaching the surface, and thereby directly heating the atmosphere in the vicinity of these particles.

b. Conduction

In this section some of the effects of the bulk properties of materials on temperature will be discussed. It is clear that the ability of a material to conduct heat away from the surface will affect the temperature at the surface. It is also clear that the amount of heat required to raise the temperature of a material by a specific amount affects the final temperature achieved by the object. This property is called the specific heat per unit volume. The ability to conduct heat is called thermal conductivity. Table C-II presents some values of these properties for different materials. Inspection of the units used for thermal conductivity shows that the temperature gradient is also an important factor in conducting heat. For a given thermal conductivity the amount of heat flowing is directly proportional to the temperature gradient. If the temperature is uniform in a body there will be no heat flow.

In Table C-II we see that air is easy to heat but is the worst conductor of heat. Water has a high specific heat and is a better conductor of heat than air. When water and air are extensively mixed in a material, the thermal properties of the mix are significantly altered. Three examples are found in the table. The conductivities and specific heats of wet sand, wet clay, and wet moorland are significantly higher than for the corresponding dry materials.

The combination of high specific heat and high thermal conductivity tends to reduce the magnitude of surface changes in a material. High thermal conductivity causes a rapid transport of heat between the surface and the interior of the material. Therefore, an even larger thermal conductivity means that the surface temperature need not be

Table C-II

VALUES OF THERMAL CONDUCTIVITY AND SPECIFIC HEAT PER UNIT VOLUME FOR SOME COMMON MATERIALS (Geiger, 1965)

Type of Material	Specific Heat for Unit Volume (cal cm^{-3} deg^{-1})	Thermal Conductivity (cal cm^{-2} sec^{-1}/deg cm^{-1})
Silver	0.59	1000
Iron	0.82	210
Concrete	0.5	11
Rock	0.43-0.58	4-10
Ice	0.46	5-7
Wet sand	0.2-0.6	2-6
Wet clay	0.3-0.4	2-5
Old snow (density 0.8)	0.37	3-5
Still water	1.0	1.3-1.5
Wet moorland	0.6-0.8	0.7-1.0
Dry clay	0.1-0.4	0.2-1.5
Dry sand	0.1-0.4	0.4-0.7
New snow (density 0.2)	0.09	0.2-0.3
Dry wood	0.1-0.2	0.2-0.5
Dry moorland	0.1-0.2	0.1-0.3
Still air	0.00024-0.00034	0.05-0.06

raised so high to transport any added heat to the interior of the material. A higher specific heat requires that more heat be added to raise the temperature of a given volume of material by a given amount. Thus if a certain amount of heat is added to some volume of a low specific heat material the temperature may rise quite high; the same amount of heat added to the same volume of high specific heat material may produce only a slight rise in temperature. Similar arguments hold for cooling processes.

c. Convection

In fluids most of the transfer of heat is accomplished by convection. When surface temperatures rise, the air in contact with the surface heats, becomes less dense, and rises; cooler, denser air sinks to take its place. This continues for as long as the surface is warmer

than the air above it. The reverse case should be mentioned because it is quite important at night. When the surface is cooler than the air, the air loses heat to the surface and hence the air cools and becomes more dense. This denser air tends to stay where it is rather than move up to allow warmer air to sink to the surface and lose its heat. Where the warm surface encourages mixing of heat through a deep layer, the cold surface discourages this. The cool air remains at the surface and continues to cool until it equilibrates with the surface. The air at higher levels may remain warmer resulting in what is known as an "inversion," i.e., a temperature rise with height, rather than the more common decrease of temperature with altitude.

Other convection-like mechanisms can cause heat transfer in fluids. Any process which causes stirring of the fluid will result in a net transfer of heat if there is a temperature gradient, or more precisely, a gradient of potential temperature. Thus if the air moves over a rough surface, significant up-and-down motions can be introduced that will transfer heat from warmer areas to cooler ones. Such mixing is enhanced by rapid decreases of temperature with height and, as already indicated, retarded by a stratification of warmer air over the cooler air.

d. Advection

Air also moves horizontally. In fact air moves horizontally to a greater extent than it does vertically. If the air in a given location is being continually displaced by air from another location, other mechanisms which might be adding or removing heat could be nullified by the influx of large quantities of air which had been affected by other heating or cooling mechanisms. Thus advection of air from one location to another is an important factor in determining the prevailing meteorological conditions.

2. Factors Affecting Temperature Measurements

Studies of the atmosphere normally begin with observations, the nature of the observations being dependent on the phenomena to be investigated. The spatial scale of meteorological and climatological phenomena varies from inches to thousands of miles and the time scale from

Table C-III

SPATIAL SCALES OF METEOROLOGICAL PHENOMENA (after Tepper, 1959)

Spatial Scale	Characteristic Dimension	Examples	Optimum Observational Spacing
Macroscale	>300 mi	Cyclones Anticyclones Frontal systems Widespread precipitation	100-300 mi
Mesoscale	10-100 mi	Land-sea breezes Squall lines	10-30 mi
Local scale	0.1-10 mi	Cloud patterns Tornadoes Local thunderstorms Urban heat-island	1/4-1 mi
Microscale	0.1-1000 ft	Turbulence Airflow around buildings	inches-feet

seconds to the centuries between ice ages. Table C-III summarizes the major divisions of spatial scale for meteorological entities. The demarcation between scales is not clearcut, and thus there are gaps and overlaps. According to the table, urban meteorological phenomena would generally fall under the local scale.

Careful inspection of Table C-III suggests that the spatial scales have analogous temporal scales. Macroscale phenomena generally persist for days, whereas mesoscale features last for hours. Local scale features are often typified by durations of the order of minutes to hours, and microscale phenomena are accompanied by rapid fluctuations which may last only a few seconds.

The small-scale, short-period changes of microscale phenomena are of little interest in studies of larger scale events. In fact microscale fluctuations can obscure the features significant to the larger scales. On the other hand, observations taken hundreds of miles apart and at six or twelve hour intervals would not be very revealing of the diurnal changes in an urban heat-island, although such observations are excellent for the study of macroscale circulations.

Coupled with the notion of scale is the appropriateness of an observation to the proper scale. An observation should be characteristic of the time and place at which it is taken and be of the scale for which it is to be used. As an example, an observation which is to be used for macroscale studies should be characteristic of an area of perhaps hundreds of square miles. By characteristic, we mean that the observed value should occur commonly within the area to be typified or be near the average of all the values within that area. For most macroscale purposes the observations should be characteristic of the large open spaces between cities. Therefore, the open spaces at airports where the observations are usually taken are quite logical choices for macroscale purposes. On the other hand, airport observations do not necessarily typify conditions within the tens to hundreds of square miles of a city.

Just as the observations should accurately characterize the area which they are supposed to represent, they should also accurately represent some appropriate time period. For macroscale phenomena this period should probably be of the order of several minutes, for mesoscale and local scale studies the appropriate time scale might be fractions of a minute to a few minutes. For microscale features, observations should represent time intervals of seconds or less. The most common approach to the problem of making an observation representative of the proper time interval is averaging. This can be accomplished by smoothing graphical records, performing electronic integration, or using instruments which respond slowly to changes in the measured variable.

As an illustration, a temperature sensing element must first reach the temperature of its environment and then indicate its own temperature. This lag time may vary from 5 minutes for mercury in steel thermometers to about one minute for mercury in glass thermometers; for some thermocouples the lag time may be only fractions of seconds. Temperature fluctuations are not detected if they are of a smaller time interval than the instrument's lag time. Thus, by selecting a thermometer with a suitable lag time the short-period temperature fluctuations can be smoothed out.

One final factor of importance in meteorological investigations is that the temperature measured should be the temperature of the air. The fact that a thermometer indicates its own temperature has already been mentioned. For the thermometer to measure the air temperature, it must be in thermal equilibrium with the environmental air. If it is in radiative equilibrium with the sun, the reading will be too high, and if it is in equilibrium with the night sky, the reading will be too low. The instrument should be shielded from radiation. New environmental air should be brought within the shield so that it will not have time to heat or cool to some temperature different from the ambient. The ventilation may be either natural or forced. However, forced ventilations may upset local stratifications.

Since many meteorological studies are concerned with the variations of atmospheric parameters in space and time and involve comparisons of values obtained on different occasions at different locations, we should be certain that the compared values are in accord with the factors discussed in this section. Scale, both spatial and temporal, representativeness, lag, and exposure are almost as important to the interpretation of meteorological data as are the more obvious factors of accuracy and precision.

3. Urban Effects on Temperature

a. City Morphology

The definition of a city depends on the discipline defining it. For meteorological purposes, the important factors are morphological. It is morphology which most affects the energy transformation and transfer processes discussed in the previous sections. Energy input from human activities may be important under some circumstances, but insolation is usually the dominating energy source and the morphology of the land surface is the principal non-meteorological factor controlling the disposition of the sun's energy.

Determination of the nature of the land surface and the structures which cover it is not always easy. Much can be learned from interpretation of aerial photographs and infrared mappings. Most larger

American cities have Sanborn* maps available which give a detailed mapping of the materials used in buildings throughout the city. Topographic maps issued by various Government agencies show the general outlines of different types of ground cover: built-up, forest, swamp, etc. In addition, there are statistical summaries of land usage such as those devised by Bartholomew (1955).

Table C-IV gives a summary of the land usage in American cities. The areas are assigned to the different categories on the basis of the use to which ground-floor space is put. Wide variations may exist among cities, but it is interesting to note the large proportion of land area that is devoted to streets. The 14% occupied by commercial, public, and semi-public property probably represents the large concrete, brick, and glass structures typical of central and outlying commercial areas.

Table C-IV

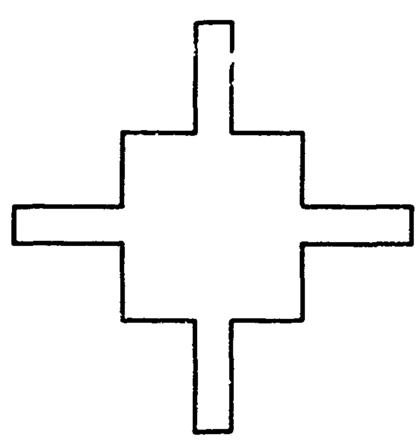
SUMMARY OF LAND USAGE IN CENTRAL CITIES
(BARTHOLOMEW, 1955)

Usage	Percent of Developed Area
One and two-family dwellings	37
Multifamily dwellings	3
Commercial areas	3
Public and semi-public property	11
Industry	6
Railroad property	5
Parks and playgrounds	7
Streets	28
Total Area	100

* Sanborn Map Company, Pacific Department, San Francisco, Calif.

The statistics give some idea of the relative amounts of space devoted to the various uses, but tell nothing about typical locations and distributions of the categories within the city. Generally there is a central business district where the city's largest and tallest buildings are located. Although called the central business district, its location is not necessarily at the center of the city. Seaport and river cities are good examples of cases where commerce and topography combine to make a city asymetric about its central business district. The central business district in the U.S. has usually developed at a major road intersection and expanded outward along the two intersecting streets. In three dimensions, the general shape is a pyramid-like figure with the irregular base approximating the quadrate cross shown in Fig. C-1. There may be secondary centers at other important intersections. Buildings at the center are generally large and multistory. Often the buildings are taller a block or two from the center.

In many cities, difficulties of access to the central area and insufficient land area for parking have led to the development of commercial centers in outlying areas. The larger ones, like downtown areas, tend to be located to take advantage of major transportation routes such



SOURCE: MURPHY AND VANCE, 1954

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FIG. C-1 GENERALIZES SHAPE OF CENTRAL BUSINESS DISTRICT IN MANY U. S. CITIES

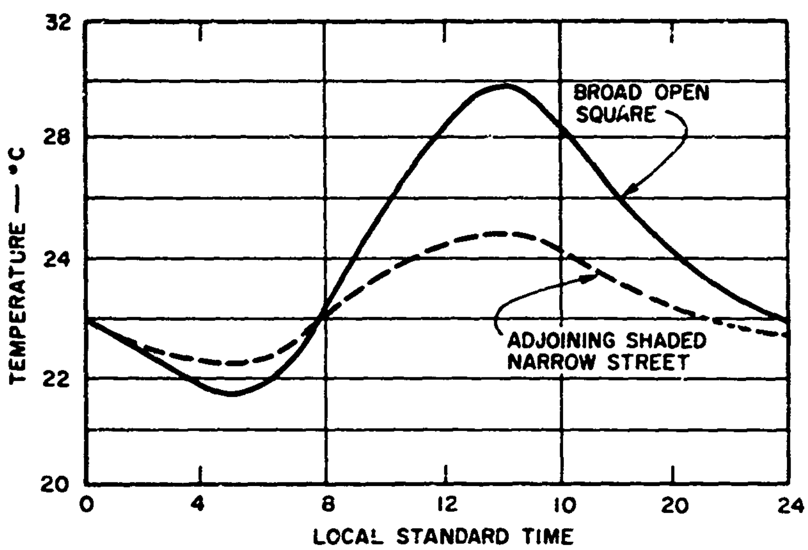
as freeways. Vast parking areas are provided, and this undoubtedly affects radiation processes. The increase in transportation via the automobile is probably the most important factor affecting commercial structure today (Vance 1962) and will very likely have a large effect on city morphology. Future cities may not have the single central business district as we know it today, but instead may have many satellite commercial centers set amid vast parking lots.

Unlike the commercial districts, the residential areas of U.S. cities do not seem to be undergoing such severe morphological changes, least in terms of those factors likely to be meteorologically important. There is a general tendency for commercial areas to displace residential areas which usually results in new residential districts of the city's periphery. The residential areas have fewer buildings than the commercial areas, and the buildings themselves are not generally as tall. Also, in most residential areas there is more vegetation than in the commercial areas.

b. Physical Effects

A flat surface will show little variation in temperature from place to place. Oceans show this uniformity, but land areas have elevation and form which cause significant variations in the distribution of temperature. Buildings can alter the elevation and form of the natural landscape and can therefore change the absorption and emission of radiant energy. The different thermal conductivities and heat capacities of buildings affect the temperature patterns produced by radiation, convection, and advection. In fact all the processes affecting temperature discussed in the previous sections are influenced by covering the landscape with man-made structures.

(1) Radiation. The effects of radiation are primarily dependent on the absorptivity and emissivity of the surface and on the exposure. Exposure depends on the slope of the surface, the direction it faces, and the presence of obstructions in the area. During the daytime obstructions shade the surface from incoming solar and sky radiation. In this respect, shade is a large factor in afternoon temperatures. Kraus (1945) gives



SOURCE: KRAUS (1945)

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FIG. C-2 DIURNAL AUGUST TEMPERATURE CYCLES IN ADJOINING OPEN AND SHADED AREAS OF VIENNA

an example of the effect of shading in city streets. Figure C-2 contrasts temperatures attained in a broad open square with temperatures in an adjoining, partly shaded street. This shading effect, he says, is responsible for the mean monthly maximum temperatures being lower in the city than in the rural areas.

Radiative cooling, as well as heating, is affected by shading. A downtown street will have a smaller net loss of radiative heat to the relatively warm surrounding buildings than will a rural plot well exposed to a cool nighttime sky. The effects of buildings on outgoing radiation are shown in Table C-V and Fig. C-3. These data come from Lauscher (1934).

For typical streets, the maximum radiation takes place from the center. Vertical walls on both sides of a street have less net radiation than one vertical surface since the two walls radiate to each other.

Table C-V shows that radiation from hilly terrain is affected by the tilt of the surface. For angles smaller than 20° from horizontal, the effects are small, causing less than a 10% reduction in outgoing radiation. For steeper surfaces, the effects are not so negligible.

Table C-V

RATIO (Parts per Thousand) OF THE EFFECTIVE OUTGOING RADIATION FROM SURFACES TO THE RADIATION FROM A FLAT, HORIZONTAL SURFACE (Lauscher, 1934)

Surface Feature	Angle, θ^{o}									
	0	5	10	15	20	30	45	60	75	90
Basin	1000	996	982	955	915	793	549	282	79	0
Slope	1000	996	986	970	951	900	796	667	528	396
Rise	1000	997	992	988	979	951	877	772	639	500
Street-a	1000	930	862	797	737	622	452	296	143	0
Street-b	1000	993	984	976	958	902	754	544	279	0

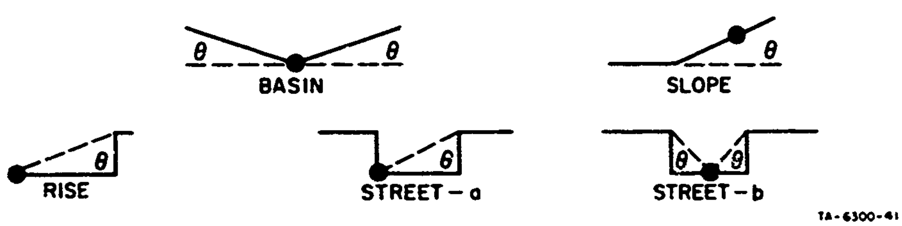
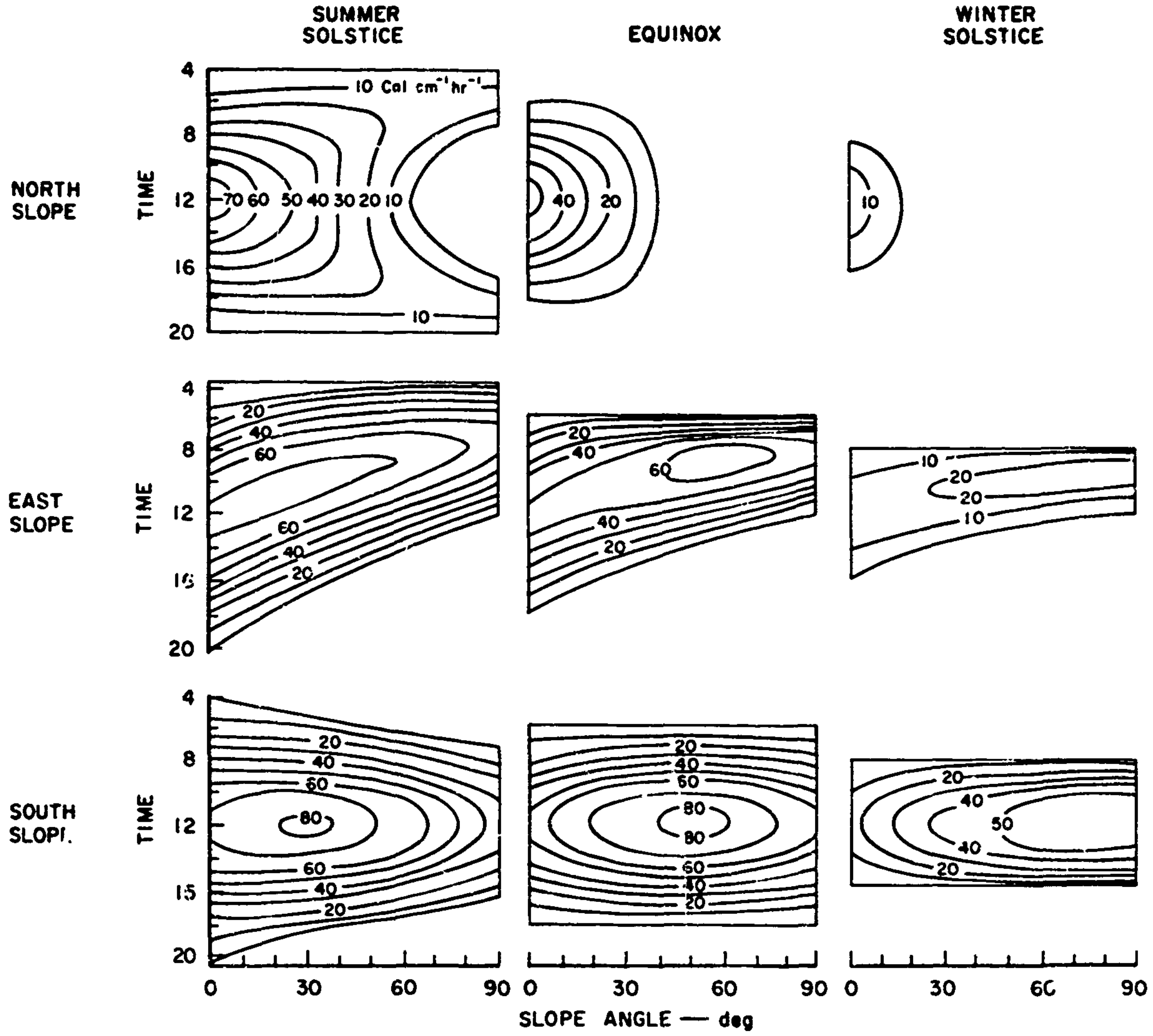


FIG. C-3 SCHEMATIC REPRESENTATION OF SURFACE FEATURES IN TABLE C-V

The effect of slope on outgoing radiation is not solely caused by back radiation from surrounding surfaces, but is also dependent on counterradiation by the mass of the atmosphere. The "thickness" of the atmosphere increases along rays nearer to the horizon. There is twice as much air along a direction 60° from the zenith as there is in the zenith direction. DuBois (1929) has calculated that the net outgoing radiation decreases from a relative value of 100 in the zenith direction to 0 in the plane of the horizon, as follows:

	Zenith					Horizon
Elevation Angle	90	70	50	30	10	0
Longwave Radiation (relative value)	100	98	93	81	51	0

The slope and orientation of a surface are also very important during the heat absorption part of the day. A north-facing slope receives very different amounts of radiation from a south-facing slope. This difference depends on time of day and season. Figure C-4 illustrates the basic relationship of slope orientation to direct solar radiation on clear days. The figure is based on actual measurements taken over a period of three years (Geiger, 1965). The abscissa is the slope angle from the horizontal. The north- and south-facing slopes show symmetrical distribution of radiation about the noon line, but the east-facing slope shows the asymmetry of the afternoon shadowing. Maximum radiation on any surface occurs on the portion most nearly perpendicular to the sun's rays. At latitude 50° the winter sun's altitude at noon is only about 15° above the horizon and its rays are perpendicular to a nearly vertical surface facing south. Maximum radiation is at noon for south- and north-facing slopes but in the early morning or late afternoon for east- and west-facing slopes, respectively. Total radiation received by east and west slopes are equal for any given day. The impression that the west slope receives more radiation stems from the fact that its temperature maximum is greater. The maximum is greater because the west slope starts its radiative heating from a higher temperature; the higher temperature comes from the convective contact with the warming morning air.



SOURCE: GEIGER, 1965

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FIG. C-4 DIRECT SOLAR RADIATION (cal cm^{-2} hr^{-1}) ON SLOPED SURFACES (50°N)

So far the discussion has been limited to direct insolation, but a significant fraction of incoming radiation is in the form of diffuse or scattered radiation. It is obvious that the taller buildings of the typical downtown area obscure a large portion of the sky from view at street level. This obscuration then reduces the amount of incoming sky radiation. Sky brightness is not uniform (see for example Coulson et al., 1960, and Ashburn, 1954), and so the amount of diffuse radiation received by a surface is affected by the orientation of the surface.

Urbanization appears to affect the radiative balance by decreasing the incoming and outgoing radiation at the street level. This means that temperatures would be cooler in the city center than in the surrounding areas during the day and warmer at night if radiative processes were the sole determinants of temperature. At higher levels in the city center, radiation is multiply reflected from the walls of tall buildings, with some absorption occurring on each reflection. This increases the effective absorptivity, adding heat at the higher levels. Thus radiation intensity at street level is diminished. In areas where buildings are three or four stories, multiple reflection and absorption take place at levels nearer the surface. Thus we might expect cooler daytime temperatures in the central downtown area and warmer temperatures in the immediate surroundings.

(2) Conduction and Specific Heat. Temperature variations in a material are strongly dependent on specific heat and thermal conductivity. High values of each lead to reduced fluctuations of temperature for given amounts of heat exchange between an object and its environment. With the large variety of materials used in the construction of buildings comes a variety of specific heats and thermal conductivities. Wood has relatively low values, whereas concrete and rock have relatively high values. The concrete, rock and metals which make up much of a typical city's downtown area generally have higher specific heats and conductivities than rural ground surfaces. Large bodies of water and some very wet soil are in the same range of values as concrete.

In unbroken soil, heat is conducted to and from lower layers very slowly. This is shown by the small temperature fluctuations at small

depths. For instance, diurnal fluctuations of less than $1^{o}C$ at a depth of only half a meter are typical. This means that most of the heat stored in the ground during the day is in the uppermost layers. However, large buildings with deep foundations or basements of thermally conductive material allow heat to transfer into greater volumes of soil, thereby allowing more storage of the day's heat. This is in addition to the heat stored in the bulk of the buildings themselves.

The relatively poor conductivity of wood and of still air means that a canopy of shade trees serves as good insulator from radiation. Thus, there are relatively wide fluctuations of temperature at the upper levels of a wooded area, but narrower fluctuations under the canopy.

Considering only the effects to be expected from urban variations of thermal conductivity and specific heat leads to the conclusion that diurnal temperature variations should be low in wooded areas and at street level in downtown areas. Areas of frame residences or open areas might be expected to have greater temperature fluctuations than downtown areas. Because the total bulk of residences is usually lower than that of larger downtown buildings, the capacity of residences to absorb and store heat should also be less. Because of this, even areas of brick or stone homes should exhibit wider temperature variations than downtown areas. The effects to be expected from variations of heat capacities in urban areas are in the same general direction as those to be expected from radiative processes. Thus daytime temperatures should be lower at street level in the city center than in the outlying areas and nighttime temperatures should be warmer.

(3) Advection and Convection. The primary mechanisms operating to minimize temperature gradients in an urban area are advection and convection. Large amounts of air moving from the countryside to the city carry the temperature of the countryside. There is some exchange of heat between the city air and the advected air. However, the area of a city is usually quite small as compared with its environs, and so the total temperature effect of the city on the country will be less than that of the country on the city.

The effects of advection are not always the same because of such factors as the diurnal cycle of wind speed. Winds are generally less strong at night, so the effects of advection would probably be greatest during the day. Since continued advection tends to minimize temperature gradients, these gradients are greatest at night.

In the same way that advection reduces horizontal temperature gradients, convection causes uniform vertical temperature gradients or lapse rates. The vertical mixing caused by convection and mechanical stirring will produce lapse rates near $1^{o}C/100$ meters. This lapse rate corresponds to the adiabatic heating or cooling accompanying the changes of atmospheric pressure in the vertical.

Vertical mixing can come about from ordinary convection initiated by the heating of the lower layers of air or from the mechanical stirring caused by obstacles in the path of horizontally moving air. Since horizontal motion and surface heating are less at night than during the day, the vertical mixing caused by them is less at night.

In addition to the large-scale horizontal motion of air over an urban area and the random vertical stirring, there is a circulation induced by the city itself. If the city is warmer than its surroundings, the warm city air would be expected to rise. As the air rises, cooler air will move in to replace it. The cooler air moving in from the perimeter of the town will be accompanied by a sinking of air outside the city. The total effect is a toroidal circulation.

It is easy to see that this toroidal circulation has the characteristics of a negative feedback system. The circulation itself tends to eliminate temperature differences by moving colder air to warmer locations and warmer air to colder locations. The greater the temperature gradients the stronger the circulation will be, and so the equalization of temperatures will be more rapid. When temperature gradients are weak, so is the circulation that tends to eliminate them.

The circulation produced by the city's heat-island is not usually a strong one. When mesoscale or macroscale winds are relatively strong, this local scale phenomenon is generally not detectable. The channeling

of low level winds into directions along streets and the eddies in the lee of large buildings also contribute to its obscuration. In spite of the difficulties, the urban heat-island circulation has been observed (e.g., Davidson, 1967, and Pooler, 1963), and it is strong enough to serve as an important counteractive force to the development of the heat-island.

(4) Other Effects. A city's activities seem to add heat to the atmosphere through combustion processes, heating and cooling devices, motor vehicles, manufacturing, and even metabolism. It has been noticed that temperatures taken at sites in a city will rise over the years as the city grows in size and population. Yet we cannot conclude that the growth of a city accounts for a temperature change unless we can separate and identify the long-term, large-scale warming and cooling trends of climate. Mitchell (1961) has made such a study and has concluded that the highest rates of urban warming are associated with the most rapidly growing cities. The relationship of city growth to long-term heating is close in the summer but not as close in the winter, suggesting that city warmth in the winter may be supported by processes different from those prevailing in the summer. Duckworth and Sandberg (1954) found that temperature increased in direct proportion to building density and that this may be the most important single factor in urban temperature effects. On the other hand, Chandler (1964) believes that changes in city temperatures are less dependent on city growth than on changes in regional climate.

In the days when the burning of coal was the principal source of heat, Schmidt (1917) calculated the release of heat from coal in the Berlin area to be 20 g cal/day-cm^2 which is of the order of solar heating during midwinter. Mitchell (1961) stated that heat produced by fuel combustion is consistent with the rural-urban temperature difference shown during the winter season. Perkins (1962) found that the total energy required to maintain the temperature difference in San Francisco agrees with the estimates of stored heat plus fuel consumption for that city.

Another relationship investigated by Mitchell (1961) was a city-county temperature difference of 1.1°F on weekdays as compared with 0.6°F on Sundays. Enlarging on this finding, Schuck et al. (1966) observed

that temperatures were lower by 0.5°F for the inland northern portion of the Los Angeles basin on weekends while the temperatures for the southern basin beach area were higher by 0.5°F, suggesting that the temperature change coincides with reduced traffic inland and increased traffic to the beach and recreational areas. Whether these temperature effects are the result of heating by automobiles or the result of radiation reaction with pollution products of the automobile is not yet answered.

Human activity can alter the composition of air through the emission of a variety of substances (gaseous, liquid, and solid) to the air. Each pollutant has its own radiative absorption-emission properties that affect the quality and quantity of absorbed radiation. For instance, the infrared absorption properties of CO_2 could cause significant warming of the atmosphere if CO_2 levels continued to rise at their present rate. However, cooling of the atmosphere could also result, because of increased albedo due to air pollution. Reflective properties of pollutants may have a large enough effect on the earth's albedo to cause a worldwide temperature drop. Since air pollution is greatest in cities, it will be there that its effects are most concentrated.

Heating devices may have a significant effect on urban temperatures during the winter, but during the summer, the amounts of heat released by such devices are generally small as compared with incoming solar heat. If the activities of man play a large role in the determination of summer urban temperature fields, it is probably through the disturbance of radiation patterns. Air pollutants may cause the air and the underlying surfaces to absorb (or reflect) radiation in different ways, perhaps to a degree where temperature fields might be altered. Unfortunately, these effects are poorly understood.

(5) Combined Effects. To this point, the various factors affecting temperature differences in urban areas have been discussed separately, but of course they do not operate separately. In this section the relative magnitude of the effects from various mechanisms will be discussed. Sundborg (1951) and Chandler (1965) have provided convenient bases for such comparisons. They have taken data from Uppsala

(Sundborg) and London (Chandler) and calculated linear regressions relating urban-rural temperature differences to other meteorological parameters.

Sundborg (1951) developed two equations relating the difference between the average of temperatures at four central city locations and the average of two open country readings. The six temperatures involved in each case were simultaneous. One equation is for daytime conditions and the other for nighttime. The equations are:

$$\Delta T_{day} = 1.4^{o} - 0.01N_{10} - 0.09u - 0.01T - 0.04e$$

and

$$\Delta T_{night} = 2.8^{o} - 0.10N_{10} - 0.38u - 0.02T + 0.03e$$

where ΔT is the difference (city temperature minus country temperature), N_{10} is cloud cover in tenths, u is wind speed (m/sec), T is some representative Centigrade temperature for the area, and e is absolute humidity (g H_2O/kg air).

Chandler (1965) has presented four equations (maximum and minimum temperature for summer and winter) based on differences of temperatures observed at one station in central London and one outside the city:

$$\Delta T_{max,s} = 0.83 + 0.03N_8 - 0.00u + 0.06T + 0.00R$$

$$\Delta T_{max,w} = 0.75 - 0.03N_8 + 0.01u - 0.00T + 0.00R$$

$$\Delta T_{min,s} = 1.72 - 0.12N_8 - 0.17u + 0.01T + 0.15R$$

$$\Delta T_{min,w} = 0.69 - 0.13N_8 - 0.10u + 0.04T + 0.08R$$

where the subscripts on ΔT refer to summer and winter maximum and minimum temperatures, N_8 is cloud cover in eighths, u is wind speed (m/sec), T is temperature (^{o}C), and R is the difference between maximum and minimum

temperature ($^\circ$C). The parameters on the right-hand side of Chandler's equations are based on values measured at the London airport.

The correlation coefficients between the values of ΔT predicted by the equations and those observed is about 0.6 for the night, or minimum temperature equations. For the day equations the correlation coefficients are 0.11 and 0.29 for Chandler's winter and summer equations, respectively, and 0.49 for Sundborg's daytime equation. These figures indicate that nighttime urban-rural differences are much better predicted by such linear equations than are the daytime values.

Chandler (1965) found no significant dependence of temperature difference on humidity. His equations for the urban-rural differences of maximum temperature show that there is little relation between ΔT and daily temperature range or wind speed. There is a slight dependence on cloudiness (a maximum effect of about 0.24°C); however, the coefficients are close to zero. The airport temperature is shown to be unrelated to the daytime London heat-island in winter. Chandler's equations indicate that there is an average urban-rural difference of about 0.8°C in maximum temperatures and this is little affected by the meteorological factors.

Sundborg's (1951) daytime temperature difference equation shows little dependence on cloud cover (a maximum effect of about 0.1°C) or temperature. The wind-speed effect is relatively strong and could reasonably be expected to reduce urban-rural temperature differences by one degree. This relatively large daytime effect may be illusory if daytime wind speeds vary only slightly from day to day in Uppsala. Meteorological data for Stockholm (65 km south of Uppsala) indicate that about 75% of the time, between 0800 and 2100 LST, summer and winter, wind speeds are less than 3 m/sec (McGill Univ., 1960 a, b). This means that the wind and cloudiness terms in the equation are generally small and comparable.

The rather large contribution of humidity to the daytime urban-rural temperature differences of Uppsala is surprising in view of the fact that Chandler found no significant effect in London. It is possible that the humidity and temperature terms principally reflect seasonal changes. The most frequent winter temperature in Stockholm (McGill

Univ., 1960 a) is about $-1^{\circ}C$ and the most frequent summer temperature (McGill Univ., 1960 b) about $13^{\circ}C$. If we take these temperatures and assume reasonable relative humidities, 80% in winter and 60% in summer, the seasonal change in absolute humidity is from about 3 g H_2O/kg air in winter to about 6 g/kg in summer. The seasonal variation of Uppsala urban-rural daytime temperature difference should be about $0.3^{\circ}C$ plus whatever variability might be introduced by seasonal variations in cloudiness. The urban-rural temperature differences would tend to be larger in winter. This contrasts with Chandler's equations for London which indicate a tendency toward greater urban-rural maximum-temperature differences in summer than in winter. The difference is about $0.2^{\circ}C$ for London plus whatever is contributed by seasonal differences in cloudiness.

Night temperature differences between a city and its environs are more closely related to meteorological factors than are daytime differences, as indicated by the higher correlation coefficients between observed and predicted values and the generally larger coefficients in the equations. All three equations, Chandler's summer and winter cases and Sundborg's night case, show a strong dependence on cloud cover, generally greater than $0.1^{\circ}C$ per one-tenth sky cover. They also show a dependence on wind speed: from $0.1^{\circ}C/m\text{-}sec^{-1}$ for wintertime London to almost $0.4^{\circ}C/m\text{-}sec^{-1}$ in Uppsala on a year-round basis. The relationship between temperature and urban-rural night temperature difference is weak. As mentioned before, Chandler found no significant humidity effects in London and Sundborg's equation shows only a weak relationship.

The rather strong dependence of urban-rural minimum temperature differences on diurnal temperature range may not be quite as significant as it first appears. The diurnal temperature range is highly dependent on cloud cover and wind speed (see for example Petterssen, 1956, p. 59) and so is the urban temperature field, as we have shown. It is not surprising then that urban-rural and diurnal temperature differences are related. However, much of the predictive capacity of the diurnal temperature range duplicates that contained in cloud-cover and wind-speed data. The diurnal temperature range might be nearly as efficient a predictor of urban-rural temperature difference as the combination of

the four parameters because the diurnal temperature range contains much of the predictive information in the other parameters.

In summary, the effects of meteorological parameters on urban-rural daytime temperature differences are small. There is substantial scatter in the data, but the center of the city typically averages about $1^{o}C$ warmer than the surrounding countryside. The effects of temperature, humidity, wind speed, cloud cover, and diurnal temperature range all appear to be small, amounting to a few tenths of a degree on the average. Also, the effects are not very systematic.

Nighttime urban-rural temperature differences are much more predictable, using meteorological parameters, than are daytime differences. The two most important factors phenomenologically related to nighttime urban-rural temperature differences are cloud cover and wind speed, and these affect radiation, advection, and convection.

Radiation depends strongly on cloud cover. When skies are clear, differences in radiation between city and country will be at their maximum. Back radiation from clouds tends to neutralize the differences and equalize the net heat loss.

Wind speed is directly connected with advection, and advection operates to eliminate temperature gradients which develop from other causes. Wind speed also affects convection. First, the horizontal air motions are converted to vertical motions as the air passes over the irregular surfaces of the city and country. This spreads the effects of the temperature gradient producing processes through a deeper layer of air so that the temperature differences are reduced.

Some of the largest temperature gradients are caused by cold air draining into basins or valleys. Such topographical cold pockets can account for rather large temperature changes in only a short distance, but the advection and convection associated with the wind will prevent their formation or will quickly eliminate these pools of cool air.

B. Humidity

Atmospheric water vapor content, or absolute humidity, is defined in several ways. These include ratios of the mass of water vapor in a given volume to the mass of moist air or of dry air. In this discussion the measure used will be the vapor pressure (in millibars). The water vapor pressure is that part of the total pressure contributed by the gaseous phase of the water.

Relative humidity, unlike absolute humidity, is strongly dependent on temperature. Relative humidity is the ratio, expressed in percent, of the water vapor pressure to the saturation vapor pressure. The saturation vapor pressure is essentially a measure of the maximum amount of water vapor which the air can hold. The higher the temperature, the more moisture the air can absorb. Thus a parcel of air containing a fixed amount of water can have its relative humidity lowered by raising the temperature. Fields of relative humidity are therefore very closely correlated with temperature fields. In fact the temperature changes will usually obscure the significant changes in actual moisture content. For this reason the following discussion will be devoted mostly to absolute rather than relative humidity.

1. Factors Affecting Humidity

For absolute humidity the principal controlling processes are evaporation, condensation, convection, and advection. These are indirectly related to temperature and to the processes affecting temperature and heat transfer. For instance, a very thin layer of air above a moist surface will approach saturation. If the temperature rises, evaporation will increase and the absolute humidity will rise. How much of this added water vapor gets to higher layers depends largely on convection and turbulent mixing.

At night the ground cools, generally by radiation. As the ground cools, the thin layer above it also cools and eventually the temperature may fall to the point where the air is saturated. At this temperature dew or frost formation can begin; this is the dewpoint temperature.

Again convection and turbulent mixing play an important role in determining how much heat and moisture are removed. If the cooling occurs through a substantial depth in a relatively moist atmosphere then fog forms. In fog the liquid water can be removed by settling or impaction on surfaces such as buildings or vegetation.

Most of the processes which add or remove moisture and which affect absolute humidity in the lowest tens of meters of the atmosphere occur at the surface. This is where most of the evaporation and condensation takes place. How cities affect absolute humidity can be largely explained by considering how they affect the surfaces where these processes occur.

2. Urban Effects

The most obvious effects that the surfaces of a city have are those relating to evaporation processes. The cement, asphalt, and buildings effectively seal the surface against evaporation. All the materials which typify a city are dry and essentially impervious to the transfer of moisture. When there is rainfall, it is quickly carried underground and disposed of outside the city. In the country, much of the rainfall seeps into the ground and later serves as a source of moisture, either directly or through evapotranspiration by vegetation. Thus, there is virtually no source of water vapor for evaporation at the surface in the city, but outside the city, water vapor is generally available.

The city also affects condensation processes. Condensation is generally limited to night and early morning hours when the surface has cooled below the dewpoint temperature. When condensation occurs, the absolute humidity is of course lowered. We've already discussed the nighttime "heat-island" effect of cities. This effect obviously causes differences in relative humidity. Chandler (1967) has pointed out that the heat-island may also produce differences in absolute humidity by retarding condensation in downtown areas.

Because of the effectiveness of convection, turbulent mixing, and advection in transporting and distributing moisture, surface effects are

likely to be most pronounced during periods of little wind. Thus in the daytime when winds are generally stronger, moisture might be expected to be more or less uniformly mixed through the lower layers over a fairly widespread area.

3. Types of Diurnal Cycles

There are at least four types of surface conditions and each has its own characteristic diurnal cycle of absolute humidity. As already noted, there are two types of surface to be considered: city and rural. For each type of surface, there are two pertinent conditions: there is condensation at the surface or there is not.

Wind and turbulent mixing decrease after sundown; the air begins to cool from below and becomes stably stratified. However, as long as condensation does not occur, evaporation will continue from rural surfaces, and the moisture evaporated will not be mixed through a very deep layer. Consequently, the humidity will continue to rise. As the air cools and the humidity rises, there will be less and less net transfer of moisture from the surface to the air and the humidity will become nearly constant. At sunrise, the surface and the air next to it begin to warm and there is evaporation again. Wind and turbulent mixing generally do not become effective until somewhat later, so there should be a rapid accumulation of water vapor in the lowest layers of air just after sunrise. As the wind picks up and mixing begins, the accumulated moisture at the surface will be dissipated through a relatively deep layer and the humidity will tend to fall slightly or remain nearly constant, depending on whether evaporation counterbalances mixing or not. This pattern will continue as long as the flux to higher levels through mixing exceeds or is about the same as the flux by evaporation from the surface. We would expect the mixing to balance evaporation through the morning, but when the surface is warm and the mixing has begun to decline in the later afternoon and early evening, the evaporation may dominate, the humidity will rise, and the cycle will start again.

Now, let us consider the city surface without condensation. After sundown, as the wind dies down, the air in the city tends to stagnate. Since, for this case, there is no condensation or evaporation, the absolute humidity tends to remain constant through the night. After sunrise, there is increased mixing and advection and the city then tends to follow the trends established in the surrounding countryside. Thus, in the city there should not be quite so sharp a humidity increase around sunrise because the city is without the increased evaporation which causes such a rise, and advection processes are not yet strong enough to bring the moisture in from the country. There should probably be a rise slightly later when the wind starts because of the advection of more moist country air into the city.

For the diurnal cycles without condensation we would expect daytime humidities in the city and country to be about the same. Perhaps the city would be very slightly drier because of the lack of water vapor sources within it. At night the rural humidity would gradually increase while the city would remain relatively constant. Around dawn the countryside would become appreciably more moist than the city for a brief period; then they would tend to equalize for the rest of the day.

Condensation does not usually occur during the day. Thus the daytime segments of the city and country humidity cycles would remain the same as those described above. At night the city humidity remains relatively constant, and the rural humidity gradually rises. If condensation occurs, water vapor is removed from the air in the rural areas, and lowers absolute humidity. The rate at which the humidity is lowered will generally be slow because nighttime stability inhibits the processes which transfer water vapor down to the surface where the condensation can occur.

Condensation is likely to occur in the city later than in the rural areas, if it occurs in the city at all. This is because the city tends to remain warmer through the night and thus condensation is inhibited. While the absolute humidity in the city remains relatively constant, the

rural humidity will remain very nearly constant until the onset of condensation; then it will gradually fall. Thus it is quite possible for the absolute humidity outside a city to be less than in the city.

Although some differences might be expected at night between urban and rural absolute humidities, their magnitude will be lessened by the air circulation over the city. The warmer air over the central city will tend to rise and draw in cooler country air. This circulation has already been described. Just as heat is redistributed from city to country, moisture will also be redistributed and in such a way that city-country differences will be reduced.

4. Examples

Unfortunately, there is very little data in the literature which would either confirm or refute the reasoning outlined on the foregoing pages. Kratzer (1956) has summarized much of the available information for some European cities and has found that the absolute humidity of cities averages slightly lower than for surrounding areas. This is in accord with the above, which indicates the city to be very slightly drier except for some evenings when condensation occurs in the country.

As for diurnal cycles, Chandler (1965) gives an average for Kew Observatory, located outside London in an area which "can be taken as typical of the more open, vegetation-covered parts of suburban London." This average cycle appears to be about the same as the rural case with condensation. In this case, it appears that evaporation and mixing processes counterbalance each other through the morning and early afternoon, and so there is a rise in absolute humidity around dawn but no further increase until late afternoon when there is a rise as evaporation dominates mixing. Absolute humidity decreases in the early evening, presumably with the onset of condensation.

The cycle typical of Dallas is one where humidity rises to a maximum just after sunrise. Then mixing dominates over evaporation and the humidity gradually drops to a minimum in the late afternoon. It rises slightly at night. The downtown region follows about the same pattern as the environs.

Appendix D

BIBLIOGRAPHY

Appendix D

BIBLIOGRAPHY

During the course of this work we have accumulated a large number of useful reports, papers, and books. Most are listed here. This Appendix is an extension of last year's bibliography of the previous report (Ludwig, 1967). There are many new entries representing recently published items or material which has become available to us during the past year.

Bibliographical Sources

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Chandler, T. J., The Climate of London, Hutchinson and Co., Ltd., London, 1965, p. 251-260. The emphasis in this 222-item list is on London, but many other works are also cited. Cited works cover the period 1661 to 1963 and are arranged alphabetically by author.

Geiger, R., The Climate near the Ground, Harvard University Press, Cambridge, 1965, p. 589-590. This text lists 17 items not included in Kratzer's Das Stadtklima. The most recent item cited was published in 1960.

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Chandler, T. J., Absolute and Relative Humidities in Town, Bull. Am. Meteorol. Soc. 48, 394-399 (1967). This paper presents evidence that weak winds in a city and condensation in the country at night may lead to conditions where the urban absolute humidity can be greater than the country humidity. This is one of the very few studies of urban humidity fields.

Coberly, E. D., City and Suburban Temperatures, Mo. Weather Rev. 40, 573-574 (1912). This paper summarizes investigations of urban-rural temperature differences and shows some agreement that the season of maximum differences is most likely to be the season of clearest skies.

Davidson, B., A Summary of the New York Urban Air Pollution Dynamics Research Program, J. Air Poll. Cont. Assoc. 17(3), 154-8 (1967). From air pollution studies over New York, meso-scale surface wind flow patterns show marked convergence into the urban heat island. Warmer temperatures prevail over the urban area to about 300 m, but cooler temperatures are the rule at 400 m, indicating a thermally induced circulation from rural to urban areas in low layers and from urban to rural areas in upper layers.

De Marrais, G. A., Vertical Temperature Difference Observed over an Urban Area, Bull. Am. Meteorol. Soc. 42, 548-54 (1961). One year's temperature difference records from a 524-foot tower in downtown Louisville were analyzed and found to show that vertical temperature differences are strongly affected by an urban area. Diurnal changes in stability are smaller in an urban area than in a rural area.

Dirmhirn, I., Local Climatic Measurements in Vienna, in Biometeorology, Vol. 2, Part 2, S. W. Tromp and W. H. Weihe, Eds., Pergamon Press, Ltd., London, 1967, p. 598-600. This article gives a brief list of studies made of the urban climate of Vienna. Recent studies include topics on interiors of houses and courtyards.

Dobson, G.M.B., Some Meteorological Aspects of Atmospheric Pollution, Quar. J. Roy. Meteorol. Soc. 74, 133-143 (1948). The interplay of meteorological conditions and air pollution produced in cities by the burning of coal is discussed.

Duckworth, F. S., and J. S. Sandberg. The Effect of Cities upon Horizontal and Vertical Temperature Gradients. Bull. Am. Meteorol. Soc. 35 (5), 198-207 (1954). Thirty-five evening temperature surveys were made, using automobile traverses in San Francisco, San Jose, and Palo Alto. Vertical gradients to 1000 feet were also measured using a wiresonde. This paper discusses the results of the measurement program and relates the intensity of the urban heat island to city size.

Dudley, L., How to Doctor the Climate Your House Lives In, House Beautiful, May 1955. Practical hints are given for planning climate control by applying basic microclimate principles.

Dyke, R. A., Nocturnal Temperature Inversions near the Gulf Coast, Mo. Weather Rev. 57, 500-2 (1929). This paper summarizes some minimum temperature measurements made at four different locations in New Orleans.

Eaton, G. S., High Relative Temperatures of Pavement Surfaces, Mo. Weather Rev. 47(11), 801-802 (1919). Two graphs are presented. One graph shows the time variation of surface temperatures for various types of paving materials exposed to sunlight while the other graph shows air temperature taken at several levels above an asphalt surface.

Frederick, R. H., A Study of the Effect of Tree Leaves on Wind Movement, Mo. Weather Rev. 89, 39-44 (1961). Wind flow studies near deciduous trees show that wind increases by about 25% and as much as 40% when the trees were removed. As leaves emerge, wind slowly decreases. This item was included because of its possible relation to ventilation and temperature.

Frederick, R. H., The Climate of Washington, J. Washington Acad. Sci. 54, 183-91 (1964). This paper reviews the sources of Washington's different types of weather, presents climatological statistics for the major meteorological elements, discusses some major meteorological events, and presents a brief discussion of the distribution of temperature within the Washington area.

Garnett, A., and W. Back, An Investigation of Urban Temperature Variations by Traverses in Sheffield (1962-1963), in Biometeorology, Vol. 2, Part 2, S. W. Tromp and W. H. Weihe, Eds., Pergamon Press, Ltd., London, 1967, p. 601-607. Temperature traverses were made over very hilly terrain to obtain data showing that relief, urbanization, and human activity have the greatest influence on the temperature field during clear, calm nights.

Geiger, R., *The Climate Near the Ground*, Harvard University Press, Cambridge, 1965. This is a standard reference in the field of microclimatology and covers a wide variety of topics. Of particular interest in this list are the chapters on the influence of topography on microclimate and the relations of man and animals to microclimate. The latter chapter contains a section on city climate. This book was also cited in the list of bibliographic sources.

Gilliam, H., *Weather of the San Francisco Bay Region*, University of California Press, 1966, 72 p. This is a nontechnical discussion of the types of weather observed in the San Francisco Bay area and the variability of climate from one part of the region to another.

Gold, E., Smog: The Rate of Influx of Surrounding Cleaner Air, Weather (London) 11(7), 230-232 (1956). This paper theorizes there is an urban circulation with rising air over the city and return flow at low levels from the rural surroundings.

Hilst, G. R., and N. E. Borone, A Study of the Diffusion of Aerosols Released from Aerial Line Sources Upwind of an Urban Complex, Final Report, Vols. I and II, prepared for U.S. Army Dugway Proving Ground, by the Travelers Research Center, Inc., Hartford, Conn., 1966. This study of diffusion includes some data on vertical and horizontal temperature fields in an urban area.

Hutcheon, R. J., R. H. Johnson, W. P. Lowry, C. H. Black, and D. Hadley, Observations of the Urban Heat Island in a Small City, Bull. Am. Meteorol. Soc. 48, 7-9 (1967). This paper describes the heat island observed in Corvallis, Oregon (pop. 21,000), for a winter and a spring night during 1966. Differences of 6 to 10°F were observed between the town center and the surrounding countryside.

Kratzer, P. A., *Das Stadtklima*, Friedr. Vieweg and Sohn, Braunschweig, 1956; English translation by American Meteorological Societv for U.S. Air Force Cambridge Research Lab., L. G. Hanscom Field, Bedford, Mass., DDC No. AD 284 776. This is the most complete work in the field; as already noted above, its bibliography is the most extensive available. The following subjects are covered in depth: aerosols and air pollution, city effects on insolation, temperature variations, city wind systems, urban humidity, and precipitation.

Kraus, E , Climate Made by Man, Quar. J. Roy. Meteorol. Soc. 71, 397-412 (1945). This review article discusses man's biological climate, his clothing, homes, and towns.

Landsberg, H. E., The Climate of Towns, in *International Symposium on Man's Role in Changing the Face of the Earth*, W. L. Thomas, Ed., University of Chicago Press, 1956, p. 589-606. This review article covers many of the ways in which cities alter the climate. After brief discussions of the history of the subject, the difficulties in determining urban meteorological effects, and the changes that may

cause the effects, the paper proceeds with discussions of air pollution and visibility, precipitation, temperature, humidity, cloud cover, and winds. The article was listed as a bibliographic source.

Landsberg, H. E., Physical Climatology, 2nd ed. revised, Gray Printing Co., Inc., DuBois, Pa., 1964, 446 p. This is a general text on climatology. Of interest to this program are the brief discussion of instrument shelters and the somewhat longer section on the influence of human settlements on climate. This discussion is not as complete as the preceding reference.

Lawrence, E. N., Microclimatology and Town Planning, Weather (London) 9, 227-32 (1954). This is a general discussion of the effects or urbanization and other human activity on weather and climate. He stresses consideration of these effects in town planning.

Linke, F., The Climate of the Large City, Biologie der Grosstadt, Frankfurter Konferenzen für Medizinish-Naturwissenschaftliche zusammen Arbiet 4, Verlag von Theodor Steinkopff, 1940, p. 75-90. A large number of factors and their cause and effect on city climate are reviewed.

Lowry, W. P., The Climate of Cities, Scientific American 217(2), 15-23 (1967). This is a general review of the field of urban climate.

Lowry, W. P., Weather and Life, Oregon State University Book Stores, Inc., Corvallis, Ore., 1967. Chapter 14 contains 12 pages devoted to a review of "Climate of the City." Urban-rural conditions are compared.

Ludwig, F. L., Urban Climatological Studies, Interim Report No. 1, Stanford Research Institute, Project No. MU-4949-580, Contract No. OCD-PS-64-201, Office of Civil Defense, Work Unit 1235A, February 1967, DDC No. AD 657248. The author describes his temperature-humidity measuring instruments and methods of collecting and processing data, taken over three cities. Results are for summer 1966 in San Jose, New Orleans, and Albuquerque; daytime results are stressed. This report also appears in the list of bibliographical sources.

Marshall, W.A.L., London Temperatures, Meteorol. Mag. (London) 77, 54-59 (1948). This paper presents and compares the temperature differences observed at two London measuring stations.

McCormick, R. A., and K. R. Kurfis, Vertical Diffusion of Aerosols over a City, Quar. J. Roy. Meteorol. Soc. 92, 392-396 (1966). This work describes the experimental determination of air flow over a city. The authors conclude that while wind speed and surface roughness affect the level of diffusivity, its variability is a response to the magnitude and depth of convective activity.

Middleton, W.E.K., and F. G. Millar, Temperature Profiles in Toronto, J. Roy Astronom. Soc. of Canada 30, 265-272 (1936). This paper presents the results of five temperature traverses through Toronto. Presented are data from a clear summer day and the following evening, a cloudy summer evening, and clear nights in autumn and winter. The summer daytime results showed the downtown area, near Lake Ontario, to be cooler than the environs. Nighttime results showed the reverse.

Mindling, G. W., Influence of Artificial Heating on the Climate of Cities, Mo. Weather Rev. 39, 1280-1283 (August 1911). The author discounts the effect of artificial heat production and believes that higher city temperatures are due to buildings acting as barriers to the wind flow, as traps for sola energy, and as surfaces impervious to moisture.

Miller, M. E., and G. C. Holzworth, an Atmospheric Diffusion Model for Metropolitan Areas., J. Air Poll. Cont. Assoc. 17(1), 46-50 (1967). A mathematical urban diffusion model for calculating pollution concentration is explained. Application of the model is difficult for night hours when the heat island is well developed and urban mixing depth is not easily determined from rural meteorological information.

Mitchell, J. M., Jr., The Thermal Climate of Cities, Symposium: Air Over Cities, R. A. Taft Sanitary Engineering Center, Cincinnati, Tech. Rep. A62-5, 1962, p. 131-145. The heat island and its apparent intensification with urban growth are discussed along with possible contributory causes. The effects of the heat island on lapse rate and turbulent mixing are also briefly considered.

Mitchell, J. M., Jr., The Temperature of Cities, Weatherwise 14, 224-229 (1961). This is a revised version of the preceding paper.

Munn, R. E., Descriptive Micrometeorology, Academic Press, New York, 1966, 245 p. This book contains a chapter which discusses the effects of cities on temperature, humidity, and wind.

Munn, R. E., and I. M. Stewart, The Use of Meteorological Towers in Urban Air Pollution Programs, J. Air Poll. Cont. Assoc. 17, 98-101 (1967). Wind and vertical temperature differences measured on towers in Montreal, Ottawa, and Sarnia, Canada, are presented and discussed. The locations are built-up, suburban, and rural, respectively, and the results give some insight into the effects of cities on lapse rates.

Palmer, A. H., Is the Heat Generated by Great Cities Changing Their Climates?, Mo. Weather Rev. 39, 1284-1286 (August 1911). The author presents data to support his stand that heat generated by great cities does not change their climate appreciably.

Parry, M., The Climates of Towns, Weather (London) 5, 351-356 (1950). This is a brief review article concerned with the influence of man's activities on the climate. The town is considered as an example of the modification of the natural surface.

Parry, M., Local Temperature Variations in the Reading Area, Quar. J. Roy. Meteorol. Soc. 82, 45-57 (1956). This paper describes the results of an 18-month survey of temperatures using a close network of stations in the Reading, England, area. The results are related to local conditions, relief, and urbanization. Differences of several degrees Fahrenheit were common for minima on clear nights. Maximum temperatures showed little variation.

Parry, M., The Urban "Heat Island," in Biometeorology, Vol. 2, Part 2, S. W. Tromp and W. H. Weihe, Eds., Pergamon Press, Ltd., London, 1967, p. 616-624. The causes of urban warmth patterns over Reading, England, were studied. The density of the built-up area was the dominant influence. Instrument exposure was found to be very important because microclimate effects dominate the temperature field in built-up areas.

Peppler, A., Zur Temperatur der Grosstädte an Heissen Sommertagen, Zeitschrift für Angewandte Meteorologie 50(8), 230-233 (1933). Temperature measurements were taken on eight clear, calm days in August 1932 in Karlsruhe. The heat island was weak during the day, but a cool island was noticed in the morning. After sunset the heat island is strong, lasting until 0730. Inflow of country air takes place at night while dust particles are noted to subside over the countryside so that heat loss in the city increases.

Pooler, F., Jr., Airflow over a City in Terrain of Moderate Relief, J. Appl. Meteorol. 2, 446-456 (1963). Wind flow during unstable atmospheric conditions was not entirely influenced by terrain. During stable periods, wind flow showed effects of topography. The inflow toward the urban center, which was noted during hours of weak winds, is of particular interest as an illustration of the effects of urban thermal patterns.

Pooler, F., Jr., A Tracer Study of Dispersion Over a City, J. Air Poll. Cont. Assoc. 16(12) 677-681 (1966). Experiments on tracer dispersion conducted in St. Louis show that daytime vertical dispersion over city and country are about the same. In the evening, vertical dispersion is much greater over the city than over open country as a result of heat-island effects.

Robb, A. D., Comparison of Temperatures from Roof and Ground Exposures at Topeka, Kansas, 1935-36, Mo. Weather Rev. 65, 388-392 (1937). This is a discussion of the effects of exposure on observed mean, maximum, minimum, and extreme temperatures at two locations in Topeka, Kansas.

Robert A. Taft Sanitary Engineering Center, Symposium: Air over Cities, Public Health Service SEC, Tech. Rept. A62-5, 1962, 290 p. The proceedings of this conference on air pollution in and about cities contains papers presented by leaders in the field. Attempts have been made to define the problems and recent findings are reported. Many of the individual papers most pertinent to urban climate are referenced separately by author elsewhere in this list.

Redway, J. W., Urban versus Suburban Temperatures, Mo. Weather Rev. 47, 28-29 (1919). A comparison is made of temperatures for New York and a suburb 17 miles away. Findings show that suburban days are warmer and suburban nights are cooler than urban days and nights.

Root, C. J., Airport and City Temperatures at Detroit, Michigan, Mo. Weather Rev. 67, 99 (1939). This paper compares mean, maximum, minimum, and extreme temperatures for two Detroit locations, based on more than four years of comparative data.

Schuck, E. A., J. N. Pitts, Jr., and J.K.S. Wan, Relationships between Certain Meteorological Factors and Photochemical Smog, Air and Water Poll. Int. J. 10, 689-711 (1966). This paper is of interest because of a postulated relation between temperature and atmospheric oxidant concentrations based on statistical evidence from the Los Angeles Basin. Other topics are also covered.

Smith, J. W., The Climate of the City and Country Compared, Mo. Weather Rev. 40(1), 30-31 (1912). The relationships of clear air, radiative heating and cooling, and urban-rural temperature differences are discussed.

Spense, M. T., Temperature Changes over Short Distances as Shown by Records in the Edinburgh District, Quar. J. Roy. Meteorol. Soc. 62, 25-31 (1936). Temperatures from Edinburgh sites of varying elevation are used to create a fictitious lapse rate. The wide range of temperature values is thought to be controlled to a degree by topographical features and the presence or absence of vegetation.

Spinnangr, F., Temperature and Precipitation in and around Bergen, Bergens Museums Arbok, Naturvitenskapelig 9, (1942). This monograph gives the results of a study of the distribution of temperature and precipitation around the coastal town of Bergen, Norway. A year of observations from eight sites are compared with a 66-year record of the Bergen permanent site in terms of meteorological and terrain features. Temperature and precipitation data (August 1941 through July 1942) for one year for each site are included.

Stanford University Aerosol Laboratory and The Ralph M. Parsons Co., Behavior of Aerosol Clouds within Cities, Joint Quarterly Report No. 3, January-March 1953, prepared for U.S. Army Chemical Corps, Contracts DA-18-064-CML-1856 and DA-18-064-CML-2282; formerly classified SECRET, declassified 1963, DDC No. AD 31509. This report contains seven analyses of St. Louis temperature fields and six of Minneapolis temperature fields. Vertical soundings of temperature are also presented. Instrumentation and field operations are described. Emphasis is on night conditions.

Stanford University Aerosol Laboratory and The Ralph M. Parsons Co., Behavior of Aerosol Clouds within Cities, Joint Quarterly Report No. 4, April-June 1953, declassified 1963, DDC No. 31508. This report has 11 analyses of Minneapolis temperature fields. Vertical temperature profiles are also presented. Nighttime conditions are stressed. Field operations are discussed.

Stanford University Aerosol Laboratory and The Ralph M. Parsons Co., Behavior of Aerosol Clouds within Cities, Joint Quarterly Report No. 6, Vol. I, October-December 1953, declassified 1963, DDC No. AD 31510. This report presents 12 analyses of temperature fields in Winnipeg and some vertical temperature profiles. Night conditions are stressed. Field operations in Minneapolis and Winnipeg are discussed.

Stanford University Aerosol Laboratory and The Ralph M. Parsons Co., Behavior of Aerosol Clouds within Cities, Joint Quarterly Report No. 6, Vol. II, October-December 1953, declassified 1963, DDC No. AD 31711. This report contains 16 analyses of temperature fields in the city of Minneapolis. The temperatures were recorded mostly during evening hours. Some vertical distributions of temperature are also presented.

Stanford University Aerosol Laboratory and The Ralph M. Parsons Co., Behavior of Aerosol Clouds within Cities, Joint Quarterly Report No. 2, DDC No. AD 7261; Joint Quarterly Report No. 5, DDC No. AD 31507. According to Mr. Donald Haines, Minnesota State Climatologist, these two reports have been declassified. These authors have not yet seen the reports, but presumably they contain more analyses of urban temperature fields.

Summers, P. W., The Seasonal Weekly, and Daily Cycles of Atmospheric Smoke Content in Montreal, J. Air Poll. Cont. Assoc. 16, 432-438 (1966). The primary reason for this paper being of interest to this program is its discussion of the effect of the city on the depth of the mixing layer. This is related to the convective dissipation of heat from the surface.

Sundborg, A., Local Climatological Studies of the Temperature Conditions in an Urban Area, Tellus II, 222-232 (1950). This article is a preliminary and abbreviated version of the following listing. It deals with the planning and conduct of an investigation of horizontal temperature variations in the vicinity of Uppsala, and presents some of

the results obtained. Regression equations are presented relating city-country temperature differences to cloud cover, humidity, wind speed, and temperature. There is one equation for daytime and another for nighttime.

Sundborg, A., Climatological Studies in Uppsala, with Special Regard to the Temperature Conditions in the Urban Area, Geographica No. 22, Universitet Geografiska Institutionen, Uppsala, 1951, 111 p. As noted in the list of bibliographical sources, this work has an extended list of references. This paper is a substantial extension of the work reported in the preceding reference. It includes a review of urban climatological literature, a description of the area around Uppsala and the general climatology of the area, a description of the instrumentation and methods used in the temperature surveys, a presentation of the observed horizontal variations in the Uppsala region, the development of regression equations to relate daytime and nighttime differences between city and country temperatures to simple meteorological elements, and a discussion of the significance of the physical factors governing urban-rural temperature contrasts.

Tinn, A. B., Local Temperature Variations in the Nottingham District, Quar. J. Roy. Meteorol. Soc. 64, 391-405 (1938). The records of eight stations in and around Nottingham are examined and used to define horizontal variations in minimum and maximum temperature. These variations are discussed and related to large-scale meteorological conditions and topography.

Wessely, E., The Breaking-In of Warm Air on 11 December 1961 in Vienna, in Biometerology, Vol. 2, Part 2, S. W. Tromp and W. H. Weihe, Eds., Pergamon Press Ltd., London, 1967, p. 625-527. This paper reports the great temperature fluctuations experienced when a cold air-warm air boundary oscillated for several hours over the inner part of Vienna.

Whiten, A. J., The Ventilation of Oxford Circus, Weather (London) 11(7), 227-229 (1956). Whiten believes that streets channel rural air into cities and large intersections (circuses) act as flues forming central cones of up-currents. Parks and open squares are reservoirs of clean air.

Wiener, F. M., C. I. Malme, and C. M. Gogos, Sound Propagation in Urban Areas, J. Acoust. Soc. Amer. 37, 728-47 (1965). This article emphasizes urban sound propagation, but there is a very brief description of instrumentation used to measure low-level vertical temperature and wind gradients in city streets. Maximum observed values of vertical temperature gradient are noted. The article repeats much of the information given in the Bolt, Beranek, and Newman report cited above.

Williams, W., Land-Sea Boundary Effects on Small Scale Circulations, Prog. Rep. No. 1, Meteorology Dept., San Jose State College, under NSF Grant GP-1363, 1964, 33 p. This report describes a program to measure the distribution of meteorological parameters in the lowest 1500 meters in the San Francisco Bay region. Preliminary results are given. The emphasis is on winds, but some examples of temperature distributions are given. The density of observations is not adequate to define the effects of local urban centers in the region.

Williams, W. A., and R. E. De Mandel, Land-Sea Boundary Effects on Small Scale Circulations, Progress Rep. No. 2, Meteorology Dept., San Jose State College, under NSF Grant GP-4248, 1966, 97 p. This report is similar in direction to the above cited report but contains more material. The network density is still too low to define the smaller scale features of the temperature field that are of most interest to this program. Most of the temperature information presented in this report is in the form of vertical cross sections.

Woolum, C. A., Notes from a Study of the Microclimatology of the Washington, D.C. Area for the Winter and Spring Seasons, Weatherwise 17, 262-271 (1964). To some extent this paper duplicates material in the previously cited paper by R. H. Frederick. The average distributions of minimum temperature, based on 13 to 19 observation sites, are presented for three 5-year periods and for the winter and spring seasons. The distribution of maximum and minimum temperatures are given for one August day and an average for the month of September, 1964. Distributions of precipitation are also presented and discussed.

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Mr. C. Donald Ahrens and Mr. Elvin Daigle contributed substantially to the execution of the field program. They shared the responsibilities of the data collection with the senior author of this report.
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13. ABSTRACT

The report gives the results of a temperature and humidity measurement program in the Dallas area during the summer of 1967. Results are presented in the form of "horizontal time sections" of temperature and absolute humidity analogous to the commonly used vertical time sections of meteorology. This mode of analysis was found to be very useful in presenting the temporal and spatial variations of temperature and humidity in an urban area. Analyses revealed that areas of densely packed 4- and 5-story buildings are the warmest parts of Dallas during the day, with the area of high-rise buildings somewhat cooler and the residential and open vegetated areas cooler still. This study confirms the presence of the warm area (or "heat-island") in the center of town at night, a phenomenon observed in many other studies. Absolute humidities in town were strongly affected by the balance between moisture release at the surface and mixing to higher levels.

Data from this program and others revealed that cities tend to be slightly warmer than their environs during the day, but this excess in temperature is only slightly related to conventional meteorological parameters. At night the magnitude of the heat-island was shown to be closely related to lapse rate in the lowest layers. Data from 78 cases were used from this program and others to develop three linear regression equations, for three city-size groups. The correlation coefficients range from -0.8 to -0.95 and the root-mean-square errors of specification from 0.7 to 1°C.

Appendices are included which describe the field study methods, present the analyses of all field data, and review the field of urban temperature and humidity effects. An 82-item annotated bibliography is also included.

DD FORM 1 NOV 65 1473 (PAGE 1)

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